AN EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF POSITION AND MOTION ON THE FREQUENCY STABILITY OF CERTAIN CRYSTAL OSCILLATORS

DONALD R. AUSTIN

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Donald R. Austin

AN EXPERIMENTAL INVESTIGATION OF THE EFFECTS

OF POSITION AND MOTION ON THE FREQUENCY

STABILITY OF CERTAIN CRYSTAL OSCILLATORS

by

Donald R. Austin

Lieutenant, Civil Engineer Corps, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
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ABSTRACT

Crystal oscillators are now available with frequency stabilities of a few parts in 10^{10} or 10^{11}. One application of such stability is in navigation systems, where geographic position may be determined by phase-comparing a received frequency-stable signal with a local frequency-stable signal. Errors may be introduced, however, by the effects of static position and of motion on the frequency stability of the oscillators employed. A testing program including static position, swinging motion, vibration, and shock tests was devised to determine the extent of such effects. The program is described and the results are presented in both tabular and graphic form.

TABLE OF CONTENTS

LIST OF TABLES

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LIST OF ILLUSTRATIONS

Figure		Page

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Figure		Page

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1. Introduction.

Due to improvements in crystal-unit and oscillator design and construction during the past ten years, it is now not unusual to speak of crystal oscillators with the capability of maintaining their frequency outputs constant to a few parts in 10^{10} or 10^{11}. Oscillators of this sort have been employed in very low frequency navigation systems, where the phenomenon of long-range, phase-stable VLF transmissions coupled with frequency-stable signals at the transmitters and aboard ship, permits a geographic position to be determined by a process of phase-comparison.

The accuracy of such a navigation system depends upon the frequency stability of the oscillators. It is recognized that environmental conditions such as temperature, vibration, and shock have a direct effect on the operation of crystal oscillators and, therefore, every effort is generally made to provide the operating conditions as specified by the manufacturer of the equipment.

In addition to the problems of temperature, vibration, and shock it was suspected that motion such as that created by the rolling and pitching of a ship or buoy might introduce instability.

It was the purpose of this investigation to determine the effects of such motion on the frequency stability of certain crystal oscillators as well as the effects of static position, vibration, and shock.

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2. Oscillators Tested.

Tests were conducted with the following oscillators:

RF Oscillator 0-76A/U
Western Electric D-175730-L2 Frequency Standard
Serial No. 43

Sulzer Laboratories Model D5 Oscillator
Serial No. 25

Sulzer Laboratories Model D5 Oscillator
Serial No. 19

Sulzer Laboratories Model D5 Oscillator
Serial No. 22

Sulzer Laboratories Model 2.5 Frequency Standard
Serial No. 256

A brief description of each type of oscillator is given in the following paragraphs. Further information may be obtained from the equipment manuals furnished by the manufacturers. [1, 6, 7].

The Western Electric frequency standard produces a frequency of 100 kilocycles which, according to the manufacturer, can be maintained constant to within approximately one part in 10^8 per day. The crystal, a GT-cut quartz plate with a very low temperature coefficient, is maintained at a constant temperature by a two-stage oven and a bridge oscillator circuit. The oscillator weighs 90 pounds; its dimensions are 19" x 20" x 10".

The Sulzer Laboratories Model D5 oscillator is a solid-state unit with a five-megacycle output and a rated stability of five parts in 10^{10} per day. The crystal is an AT-cut quartz plate, vibrating in a fifth-overtone, thickness-shear mode. Temperature level is maintained by a two-stage oven. The oscillator weighs approximately

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three and one-half pounds; its dimensions are 4¼" x 4¼" x 6 7/8".

The third type of oscillator tested, a Sulzer Laboratories Model 2.5 frequency standard, is also a solid-state unit. It has frequency outputs of two and one-half megacycles, one megacycle, and 100 kilocycles. Stability as stated by the manufacturer is one part in 10^{10} or better per day. The crystal-unit is a two and one-half megacycle military-type designed by Warner of Bell Telephone Laboratories. It is mounted in a proportionally-controlled double oven. The oscillator weighs approximately six and one-half pounds; its dimensions are 4½" x 4½" x 11 3/4".

3. Test Program.

Purpose and Procedure

The purpose of the testing program was to reveal the effects of static position, swinging motion, vibration, and shock on the frequency stability of the crystal oscillators described above. To accomplish this goal, each of the oscillators was subjected to certain conditions and combinations of position and motion while a constant observation was made of its frequency output.

The frequency standard employed as a reference for the tests was a Varian Model V-4700 Rubidium Vapor Frequency Standard with a long term frequency stability of 5×10^{-11} in any one-year period (standard deviation). To insure the reliability of the standard during the test period, its output was continually phase-compared against the 20 kilocycle signal of WWVL. This comparison was made with a Textran Series 599 VLF Tracking Receiver. The stability during the period from 23 July 1965 to 1 November 1965 was 2.3×10^{-11} (standard deviation).

The output of the test oscillator was phase-compared against the Rubidium standard and the output of the phase comparator was recorded on a strip chart recorder. The basic test system is shown in Figure 1. Examination and processing of the recorded data produced the results presented in Section 5.

Circuits and Equipment

While the test circuit was basically that shown in Figure 1, the laboratory hook-up was more complicated due to the simultaneous testing of as many as four oscillators. All phase comparisons were made at 100 kilocycles, necessitating the use of frequency dividers in the case of the Sulzer D5's with their five-megacycle outputs. The phase comparators, frequency dividers, and oscillators also required separate power supplies. Figure 2 shows an extension of the basic test system for the case of four oscillators under test.

A thermistor-bridge circuit and a chart recorder were employed to maintain a constant record of room temperature for the duration of the tests.

Swinging motion was provided by a specially constructed swinging platform shown in Figures 3 and 4. The swing was driven by a three-quarter horsepower electric motor coupled to a hydraulic transmission. The transmission permitted adjustment of swing frequency and the slotted drive wheel permitted adjustment of swing amplitude.

Vibration was accomplished with a Goodmans Model 390 A Vibration Generator. A low-frequency function generator and a power amplifier were used to supply the necessary input. The shake table with the three Sulzer D5 oscillators mounted on it is shown in Figure 5.

Figure 6 illustrates the equipment used to provide a periodic lift-and-release motion for the shock testing described in a later paragraph. The equipment consisted of a direct-current motor with a cam attached to its shaft, and geared for high-torque, slow-speed

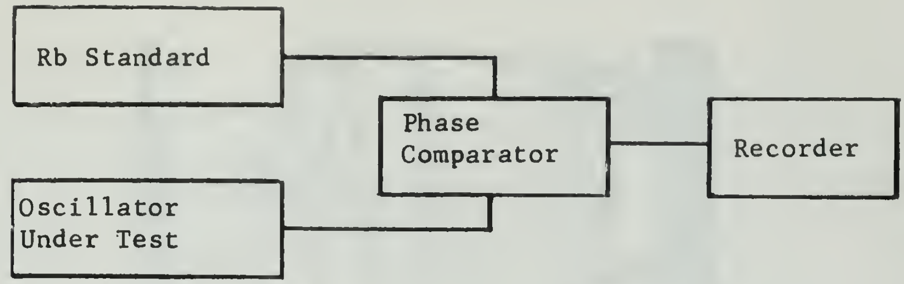

FIGURE 1

BASIC TEST SYSTEM

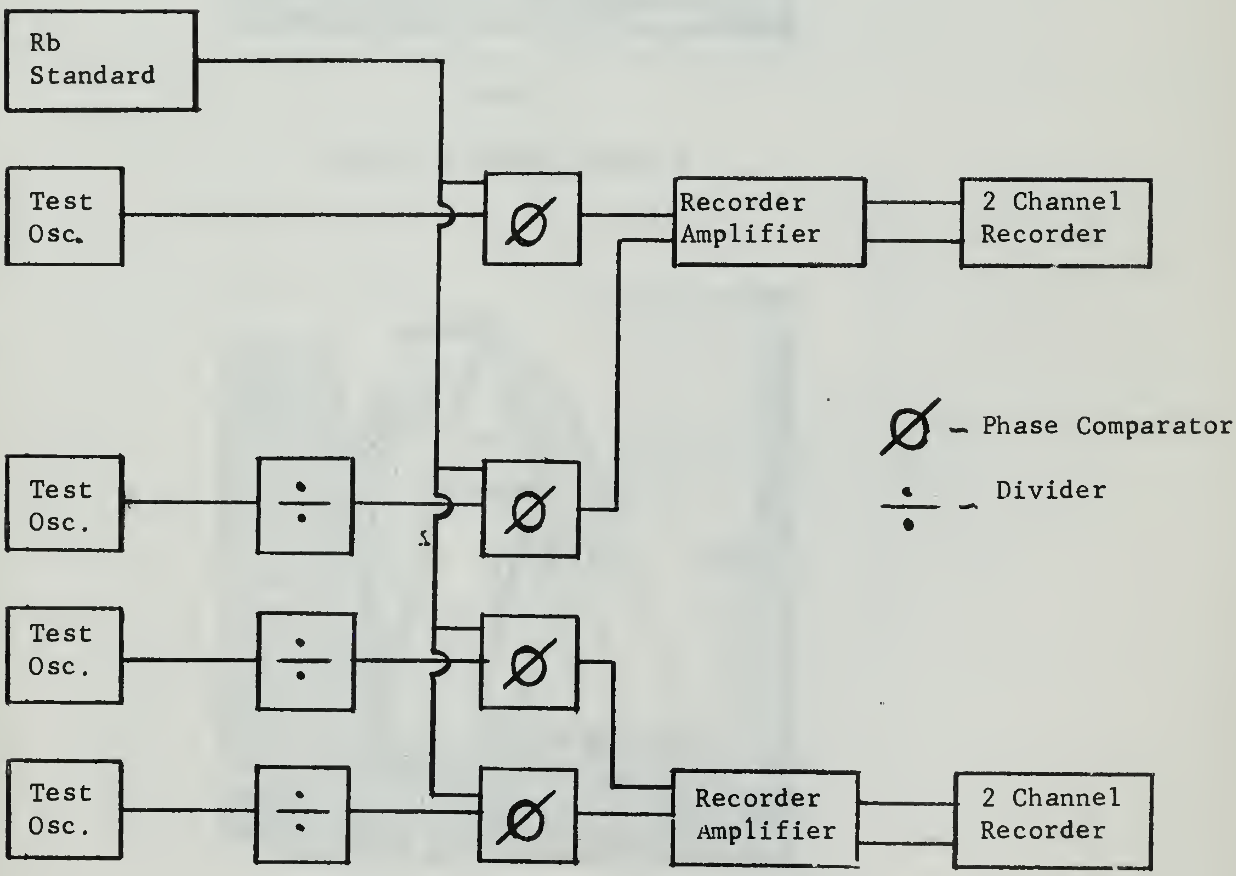

FIGURE 2

BASIC TEST SYSTEM EXTENDED FOR
SIMULTANEOUS TESTING OF FOUR SULZER OSCILLATORS

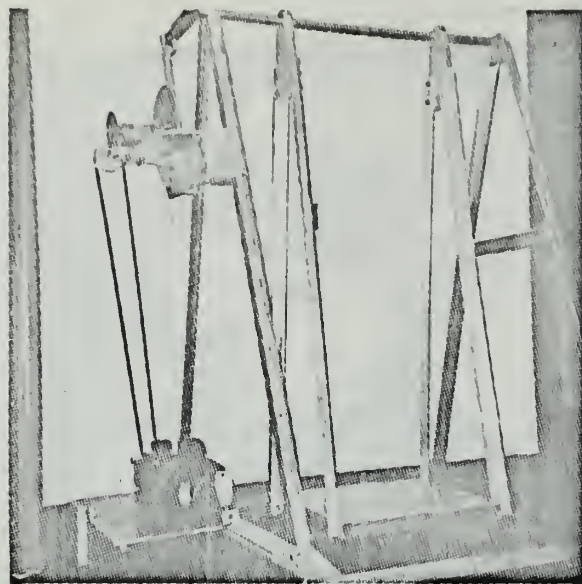

FIGURE 3

SWING PLATFORM, VIEW 1

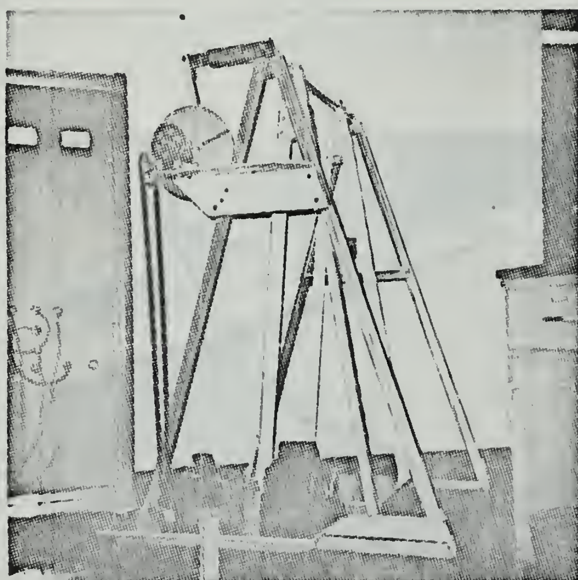

FIGURE 4

SWING PLATFORM, VIEW 2

FIGURE 5

SULZER D5 OSCILLATORS MOUNTED ON SHAKE TABLE

FIGURE 6

SHOCK TESTING EQUIPMENT

operation. The cam periodically lifted and released a hinged bar from which was suspended the mounting platform for the oscillators.

Description of Tests

Static Tests. The static tests consisted of operating the test oscillator for at least 48 hours on each of its six sides. The oscillator was operated first in its normal position, then rotated counterclockwise through the side, upside down, and side positions. It was then operated on each of the remaining two sides. After 48 hours in each of these positions, the oscillator was returned to its normal position for an additional 48 hours of testing. These tests were conducted on all of the oscillators. Table I lists the various static tests and their descriptions.

TABLE I

STATIC TEST DESCRIPTIONS

Test	Oscillator Position
Static One	Oscillator in normal operating position
Static Two	Oscillator tipped onto its side
Static Three	Oscillator tipped upside down
Static Four	Oscillator tipped onto its side
Static Five	Oscillator tipped forward onto its face
Static Six	Oscillator tipped backward onto its back

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<u>Swing Tests</u>. These tests were also conducted over a basic 48 hour test period. The test oscillator or oscillators were fastened to the swing platform and the swing was then placed in motion. The Western Electric O-76A/U was swung at various amplitudes and frequencies in one position only, the normal position, with the front panel of the oscillator parallel to the leading edge of the swing platform and perpendicular to the line of motion. The four Sulzer oscillators were swung simultaneously, and in two positions, the first being identical to that described for the O-76A/U. For the second position, the oscillators were rotated 90° in the plane of the platform. The period and amplitude of the various tests are given in Tables II and III.

TABLE II

SWING TEST DESCRIPTIONS,
WESTERN ELECTRIC OSCILLATOR

Test	Amplitude*	Period
Swing One	10°, 10°	30 seconds
Swing Two	10°, 10°	10 seconds
Swing Three	20°, 20°	30 seconds
Swing Four	5°, 5°	30 seconds
Swing Five	5°, 5°	10 seconds
Swing Six	10°, 10°	20 seconds

*10°, 10° represents a symmetric swing of 10° off the vertical in each direction.

TABLE III

SWING TEST DESCRIPTIONS,
SULZER OSCILLATORS

Test	Amplitude*	Period
First Position:		
Swing One	5°, 10°	30 seconds
Swing Two	5°, 10°	10 seconds
Swing Three	24°, 30°	30 seconds
Swing Four	24°, 30°	10 seconds
Second Position:		
Swing Five	5°, 10°	30 seconds
Swing Six	5°, 10°	10 seconds
Swing Seven	24°, 30°	30 seconds
Swing Eight	24°, 30°	10 seconds

*5°, 10° represents an asymmetric swing of 5° off vertical in one direction and 10° off vertical in the opposite direction

Vibration Test. This test was conducted only with the Sulzer D5 oscillators. The oscillators were mounted on a one-quarter inch thick aluminum plate with a diameter of twelve inches which was then attached to the vibration generator (see Figure 5). They were vibrated simultaneously at a frequency of 20 cycles per second with a force of approximately one g for a period of 12 hours. After a 12 hour quiet period, the oscillators were once again subjected to the same vibration condition for a period of ten hours.

Shock Test. The shock, or impact, test was also conducted only with the Sulzer D5 oscillators. The test consisted of a free fall from a height of three-tenths of an inch onto asphalt tile laid on

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concrete (see Figure 6). As in the vibration test, all three oscillators were tested simultaneously. Impacting occurred at a rate of once every ten seconds and was conducted continuously for 12 hours.

Environment. All tests were conducted in an open laboratory with room temperature normally ranging daily from 21°C to 23°C. Over the 43 day test period the mean temperature was 22°C with a low of 18°C and a high of 29°C.

Data furnished by Sulzer Laboratories with respect to effects of temperature change on frequency stability of the Sulzer oscillators is shown in Table IV. Similar data for the Western Electric oscillator was not available.

TABLE IV

EFFECTS OF TEMPERATURE ON
FREQUENCY STABILITY OF SULZER OSCILLATORS*

Oscillator	Temperature Change	Maximum $\frac{\Delta f}{F}$**
Model 2.5 Frequency Standard	ambient temperature 20°C changed ± 15°C	$\pm 2 \times 10^{-10}$
Model D5	ambient temperature -54°C vs + 25°C	$\pm 1 \times 10^{-9}$
Model D5	ambient temperature -18°C vs + 25°C	$\pm 5 \times 10^{-10}$
Model D5	ambient temperature +60°C vs + 25°C	$\pm 5 \times 10^{-10}$
Model D5	ambient temperature +65°C vs + 25°C	$\pm 1 \times 10^{-9}$

*Information furnished by Sulzer Laboratories

**Defined on Page 14

4. Data Acquisition and Processing.

Acquisition

During the course of each test, the outputs of the various phase comparators were fed to strip chart recorders which provided a permanent data record for processing and analysis at a later date. Temperature data was also permanently recorded. The phase-comparison data was in the form shown in Figure 7.

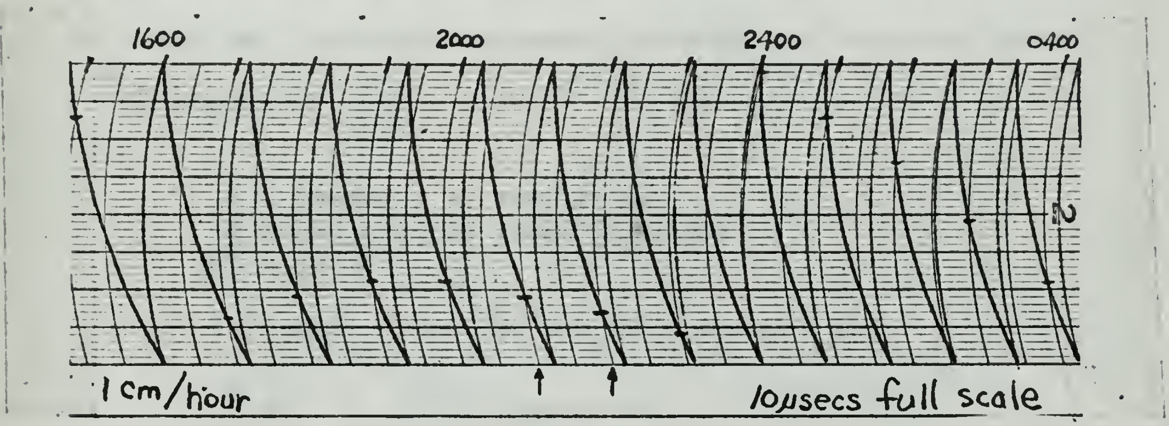

FIGURE 7

SAMPLE OF RECORDED PHASE COMPARATOR OUTPUT

The output of a phase comparator indicated the difference between the frequencies of the two input signals. If the frequencies of the signals were equal, the phase difference of the signals was constant, and the output of the phase comparator was constant. If the frequencies were not equal, however, the signals passed in and out of phase with each other periodically and the cyclic change in phase difference produced a similar variation in the phase comparator output. By recording this cyclic output on a strip-chart moving at a regulated speed, the rate of phase shift, cycles/unit time, was determined. For example, as shown in Figure 7, during the period from 2100 to 2200

the phase comparator passed through 1.05 cycles; the rate of phase shift during this period was 1.05 cycles/hour.

All phase comparison was done at a frequency of 100 kilocycles. Therefore, during the one-hour period, the standard signal went through 3600 x 100,000 or 3.6×10^8 cycles while the test signal went through $3.6 \times 10^8 - 1.05$ cycles.

The difference between the frequencies, expressed as a fraction, is called the fractional frequency error or the frequency offset. It is written as $\frac{\Delta f}{F}$ where

f = frequency of test signal
F = frequency of standard signal
$\Delta f = f - F$

The frequency offset for the above example was

$$\frac{\Delta f}{F} = \frac{-1.05}{3.6 \times 10^8} = -2.9 \times 10^{-9}$$

It is customary to refer to the amount of phase shift in terms of time rather than frequency. At 100 kilocycles, the time for one cycle is ten micro-seconds and 1.05 cycles of phase shift per hour is equivalent to 10.5 micro-seconds of phase shift per hour. The frequency offset may then also be computed as

$$\frac{\Delta f}{F} = \frac{\Delta t}{T} = \frac{-10.5 \times 10^{-6}}{3600} = -2.9 \times 10^{-9}$$

where T = period of observation in seconds
Δt = phase shift in seconds occurring during T

<u>Processing</u>

The recorded data for each test was examined in the manner outlined above. The number of micro-seconds of phase shift per hour

was noted for each hour of each test period. These figures were used to compute hourly values of frequency offset, $\Delta f/F$, which were then plotted versus time. A sample plot is shown in Figure 8. The positive values of frequency offset indicate that the frequency of the test oscillator was above that of the standard. The upward drift of the points represents an increase in frequency of the test oscillator. This is a normal condition, caused by aging of the crystal.

Next, a digital computer was employed to fit a straight line to the plotted points and to measure the dispersion of the points about this fitted line by computing their standard deviation. The program used for these computations is given in the Appendix. The slope of the fitted line represented the frequency drift rate of the test oscillator and the standard deviation of the points was an indicator of the oscillator's frequency stability, with lower values of standard deviation indicating better stability. Figure 9 shows the sample plot presented in Figure 8 with a straight line fitted to the points. The choice of a one-hour interval between the points was purely arbitrary. Figures 10 and 11 present the same data plotted at intervals of one-half hour and two hours respectively. It may be noted that the smallest variation of $\Delta f/F$ plotted in Figure 9 is 7×10^{-11}; in Figure 10, 14×10^{-11}; and in Figure 11, 3.5×10^{-11}. This is because the smallest value of $\Delta f/F$ is inversely proportional to the length of the observation interval. Using the 40-line chart paper shown in Figure 7, with the recorder calibrated for ten

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FIGURE 8

SAMPLE PLOT OF

FREQUENCY OFFSET VS TIME

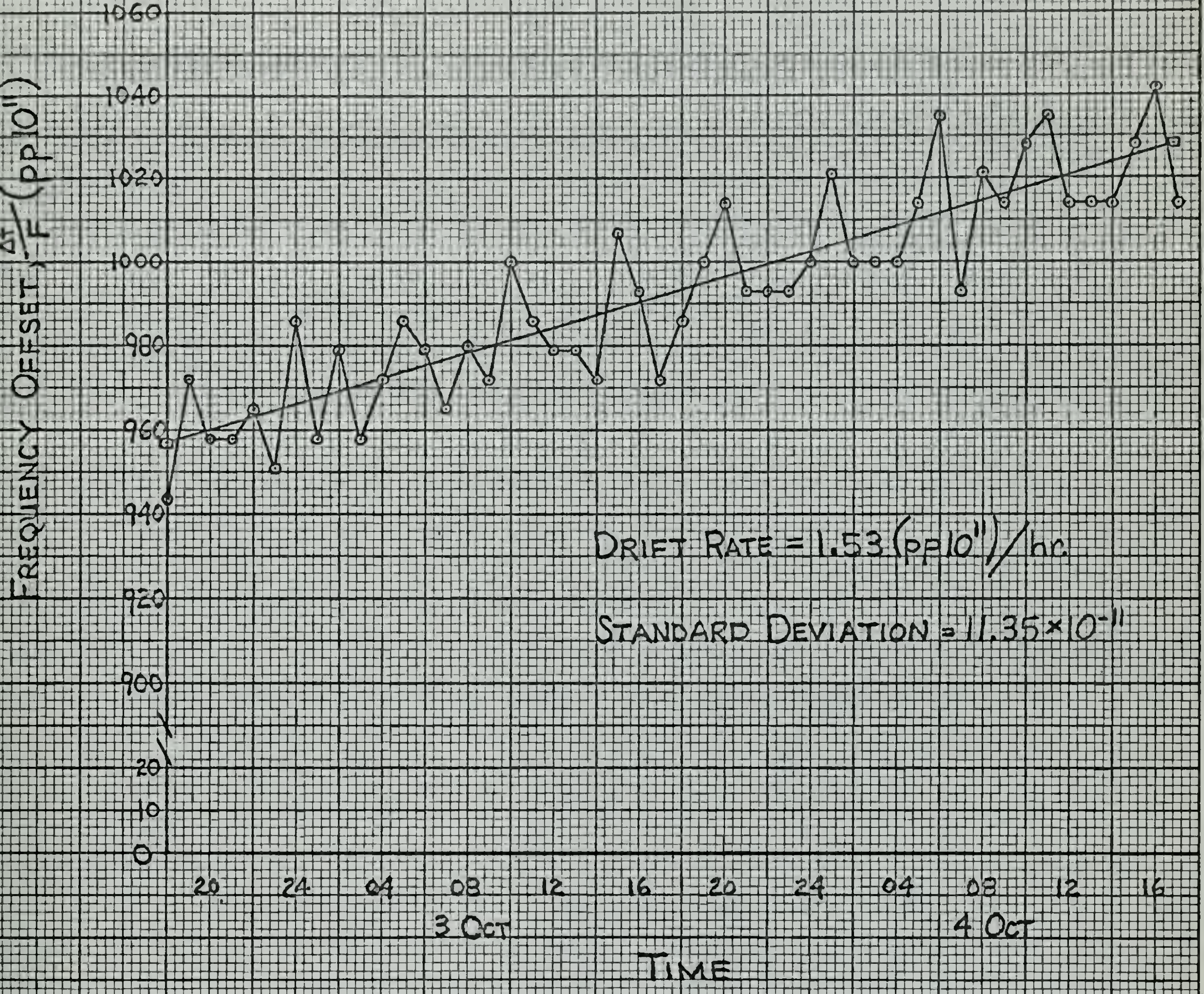

FIGURE 9

SAMPLE PLOT OF
FREQUENCY OFFSET VS TIME
WITH FITTED LINE AND
STANDARD DEVIATION,
ONE-HOUR INTERVALS

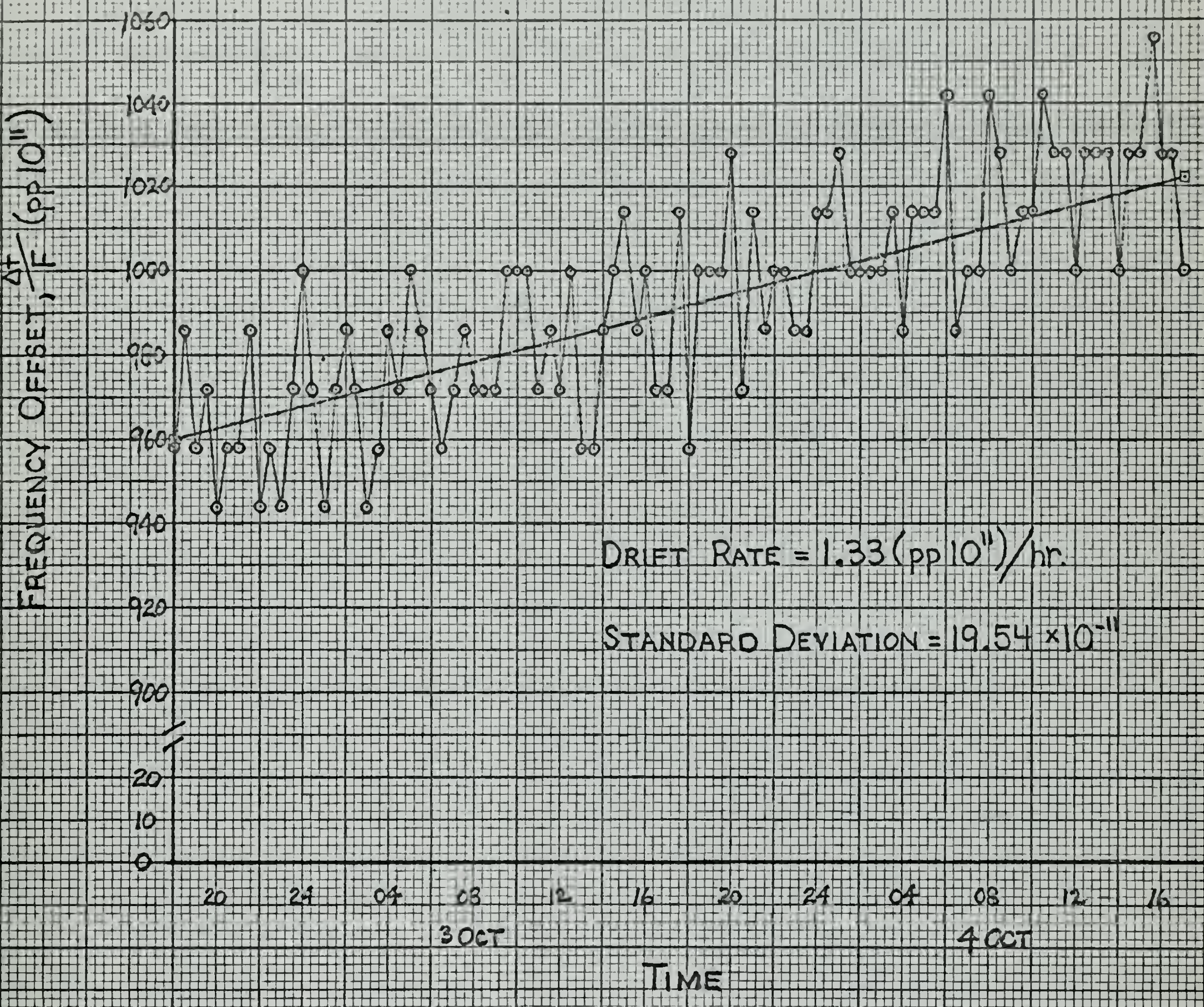

FIGURE 10

SAMPLE PLOT OF
FREQUENCY OFFSET VS TIME
WITH FITTED LINE AND
STANDARD DEVIATION,
ONE-HALF HOUR INTERVALS

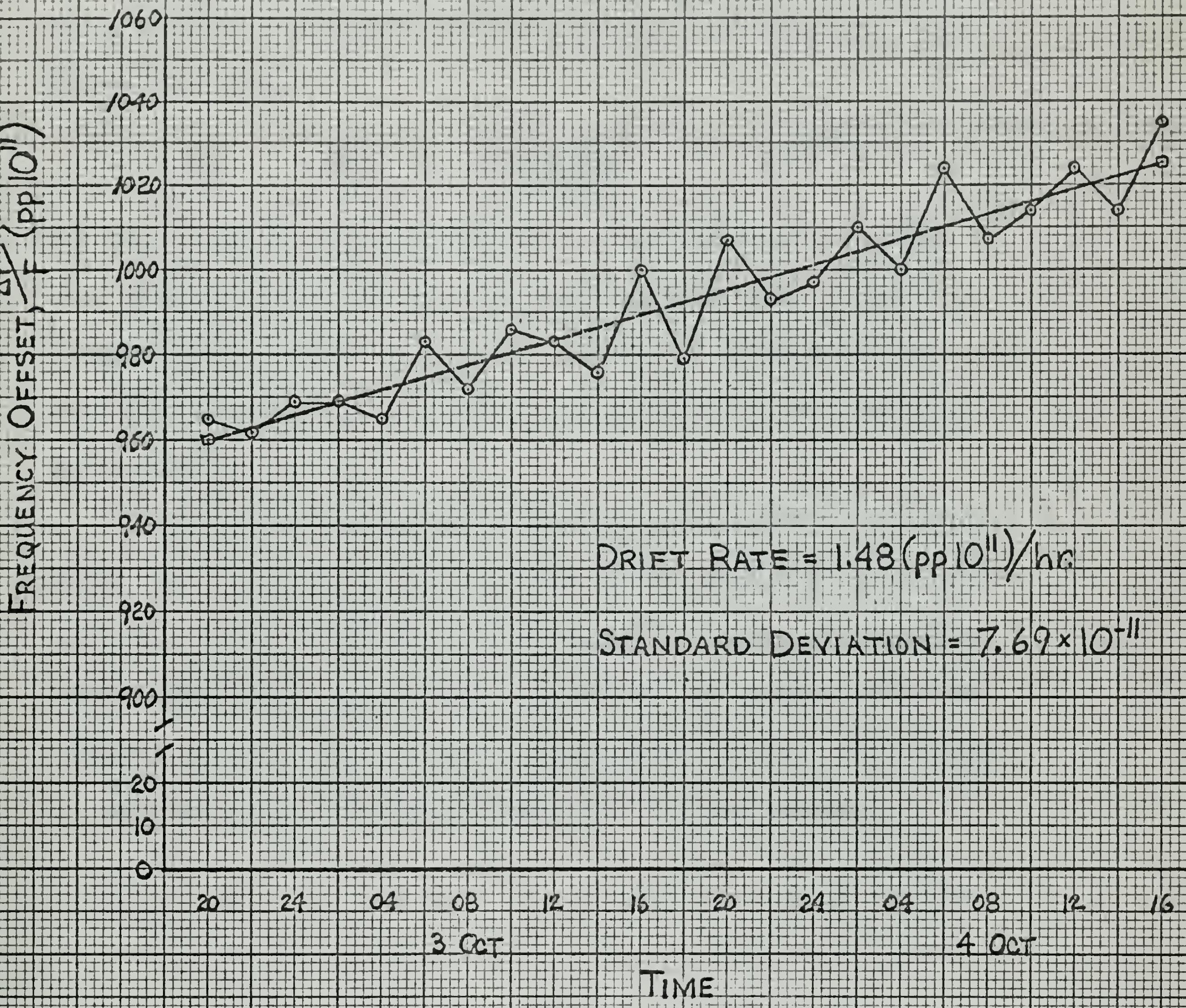

FIGURE 11

SAMPLE PLOT OF FREQUENCY OFFSET VS TIME WITH FITTED LINE AND STANDARD DEVIATION, TWO-HOUR INTERVALS

micro-seconds of phase shift for full scale deflection, the smallest increment of phase shift readable is 0.25 micro-second. Therefore, for a one-hour observation interval, the smallest value of $\Delta f/F$ (other than zero) is

$$\frac{\Delta f}{F} = \frac{\Delta t}{T} = \frac{0.25 \times 10^{-6}}{3600} = 7 \times 10^{-11}$$

For the purposes of this investigation, the choice of a one-hour observation interval proved to be quite satisfactory. Additional accuracy could have been obtained, however, by using recording equipment with 100-line paper, permitting phase shift to be read to 0.1 micro-second.

In summary, the data processing was accomplished in three steps. First, the strip charts were examined for the amount of phase shift per hour. Second, this data was converted to values of frequency offset and plotted against time. Third, to the plotted points was fitted a straight line, whose slope was thus obtained, and a measure of the variation of the points about the line was computed.

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5. Test Results.

The results of all tests are presented in Tables V through IX and Figures 12 through 37. The complete testing program of static, swinging motion, vibration, and shock tests was conducted with only the three Sulzer Model D5 oscillators. The two frequency standards were not subjected to vibration and shock.

Prior to the arrival of the Sulzer equipment, static and swinging motion tests were begun with two Western Electric frequency standards. One of these was the oscillator mentioned in Section 2, a model 0-76A/U, and the second was an earlier model, 076/U. It was soon determined that the drift rate and frequency stability of the older 0-76/U were affected by fluctuations in room temperature. The combined weight of the two oscillators (approximately 180 pounds) also proved to be too great a load for the swing platform and prevented simultaneous swing testing. A circuit failure in the 0-76/U, coupled with the problems of its poor stability and load on the swing, caused testing with this particular oscillator to be discontinued. The 0-76A/U, however, was unaffected by changes in room temperature and operated properly during the test period.

The results of the static and swing tests for this oscillator are given in Table V and Figures 12 through 15. In some instances the movement of the oscillator from one static position to another created a temporary frequency disturbance and several hours were required for the drift rate to return to its former state.

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During this recovery period the change in frequency offset was relatively rapid and therefore the total test period was divided into sections to permit better fitting of straight lines to the data points. The three highest values of drift rate plotted in Figure 12, and the three highest values of standard deviation plotted in Figure 13, occurred during the recovery periods. For reference purposes the oscillator was operated in the Static One or normal position at the beginning and end of both the static test series and swing test series. The "motor only" entry in Table V refers to a period when the swing drive was disconnected and the swing platform was at rest, but the drive motor was running. This particular test was conducted to check for possible effects of vibration generated by the motor and hydraulic transmission.

After a three-week warm-up period, the new Sulzer equipment was tested. It was recognized that this was an inadequate warm-up time, but the late arrival of the equipment and the pressure of time made it mandatory to begin the tests. The results of these tests are given in Tables VI through IX and Figures 16 through 37. The room temperature variations had no noticeable effect on the drift rate or frequency stability of these oscillators.

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TABLE V

TEST RESULTS FOR
WESTERN ELECTRIC O-76A/U OSCILLATOR
SERIAL NO. 43

Test	Condition	Length (Hours)	Drift Rate $\frac{\Delta f/F\ (pp\ 10^9)}{hour}$	Standard Deviation ($x\ 10^9$)
Static 1	normal	48	0.110	0.35
Static 2 (a)	side	24	0.473	1.05
Static 2 (b)	side	24	0.141	0.53
Static 3	upside down	48	0.143	0.87
Static 4	side	40	0.172	0.53
Static 5 (a)	front	12	0.835	1.12
Static 5 (b)	front	36	0.053	0.44
Static 6 (a)	back	6	1.494	1.11
Static 6 (b)	back	20	0.237	0.49
Static 6 (c)	back	22	0.144	0.43
Static 1	normal	48	0.102	0.82
Static 1	normal	192	0.037	0.57
Static 1	normal	158	0.025	0.41
Swing 1	10°, 10°, 30 sec.*	48	0.133	0.80
Swing 2	10°, 10°, 10 sec.	48	0.033	0.80
Swing 3	20°, 20°, 30 sec.	48	0.031	0.72
Swing 4	5°, 5°, 30 sec.	48	-0.003	0.86
Swing 5	5°, 5°, 10 sec.	48	0.047	1.29
Swing 6	10°, 10°, 20 sec.	48	-0.037	0.81
Static 1 (motor only)	normal	48	0.039	0.67
Static 1	normal	48	0.127	0.96
Static 1	normal	48	0.033	0.60
Static 1	normal	97	0.025	0.73

*10°, 10°, 30 sec. represents a symmetric swing of 10° off the vertical in each direction with a 30-second period.

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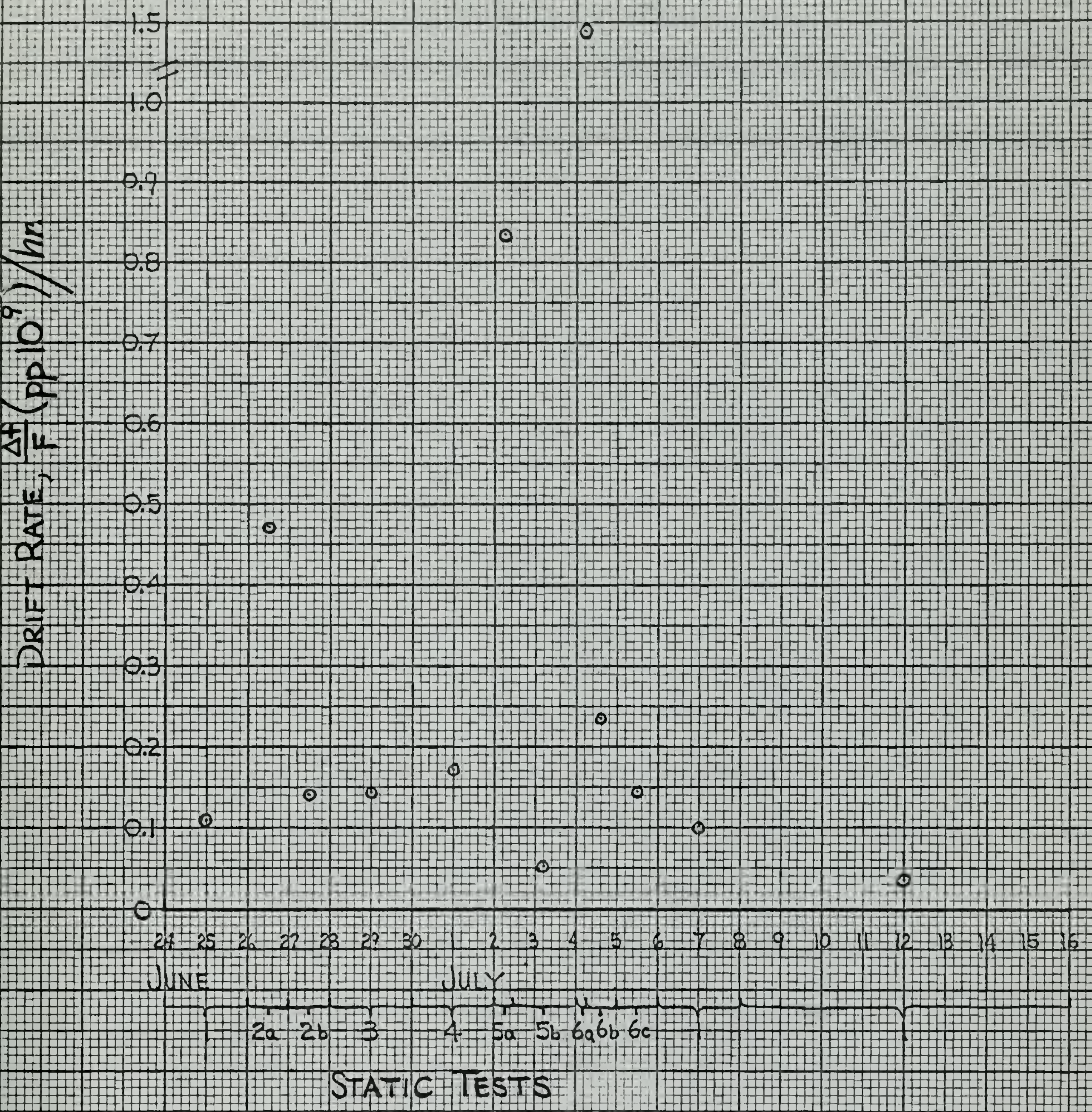

FIGURE 12

CHANGES IN DRIFT RATE OF
WESTERN ELECTRIC O-76A/U
DURING STATIC TESTS

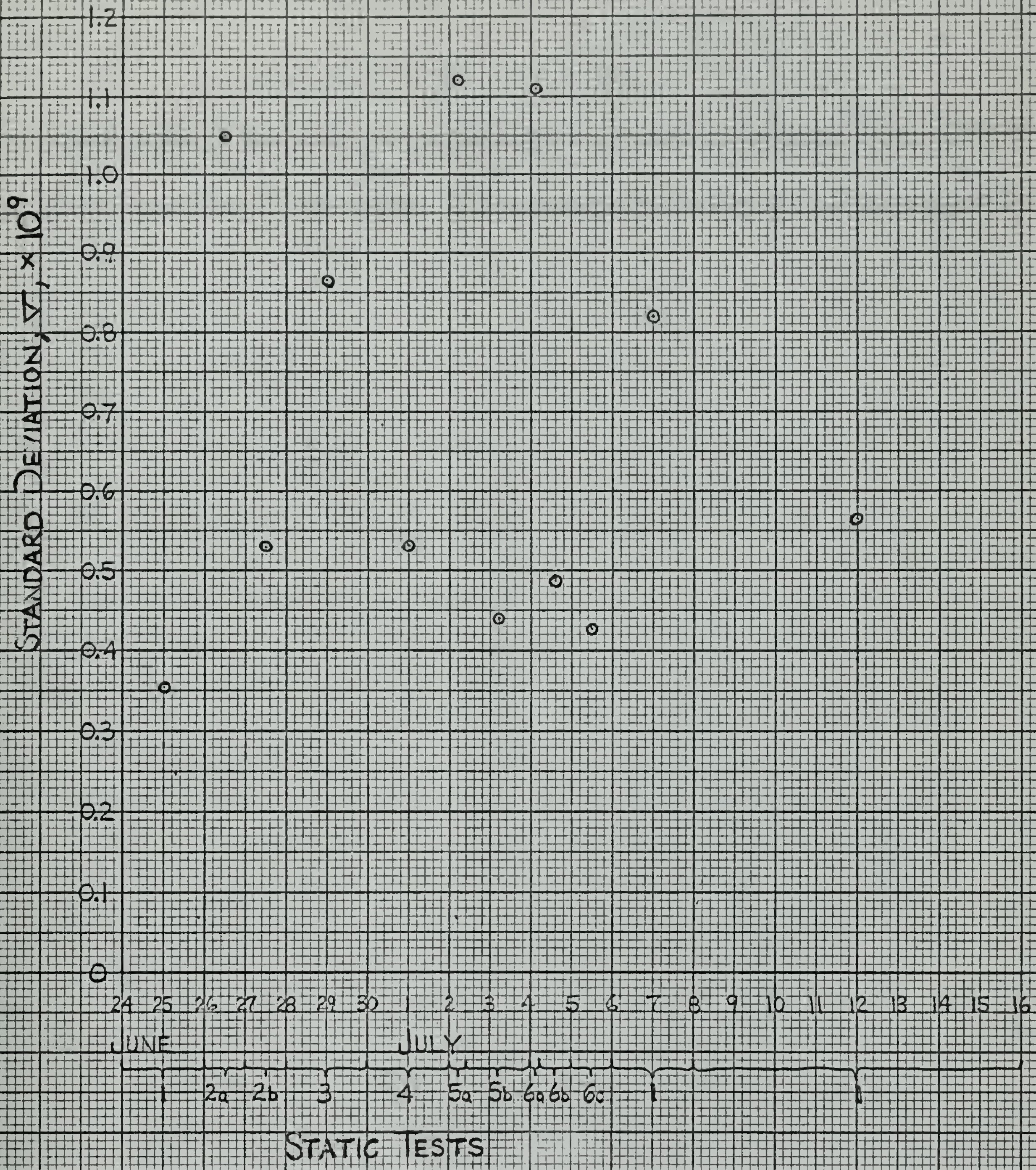

FIGURE 13

CHANGES IN STABILITY OF WESTERN ELECTRIC O-76A/U DURING STATIC TESTS

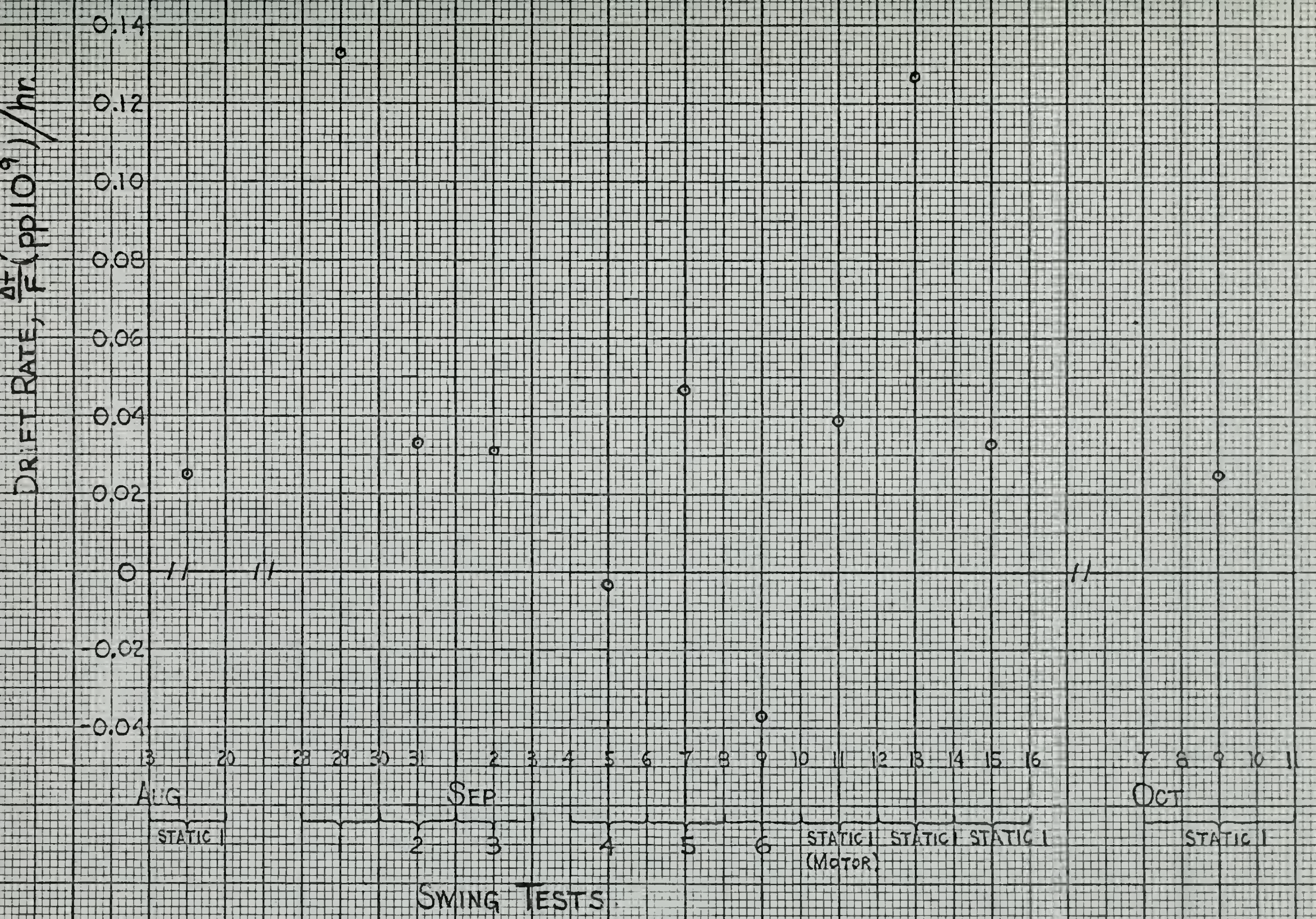

FIGURE 14

CHANGES IN DRIFT RATE OF
WESTERN ELECTRIC O-76A/U
DURING SWING TESTS

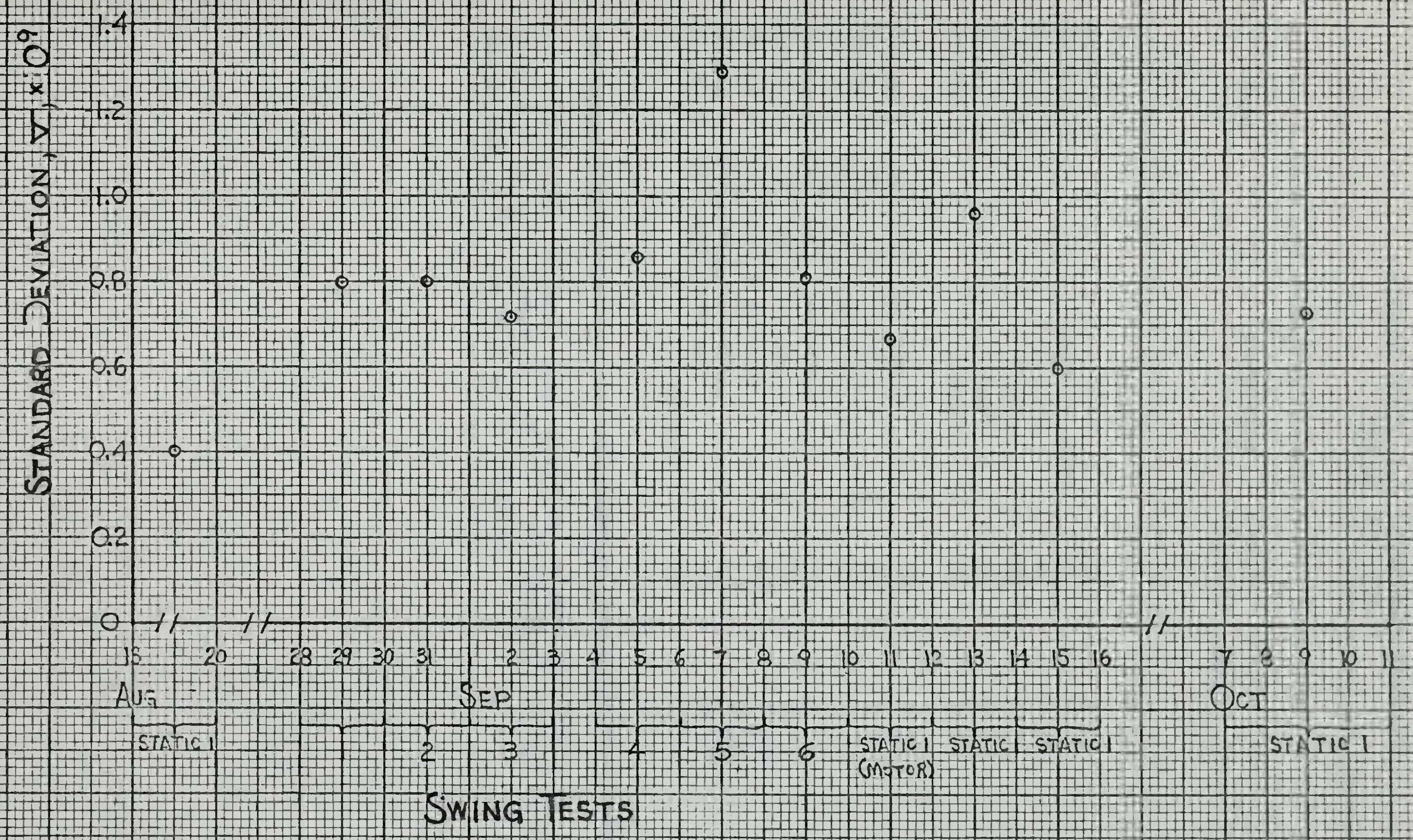

FIGURE 15

CHANGES IN STABILITY OF WESTERN ELECTRIC O-76A/U DURING SWING TESTS

TABLE VI

TEST RESULTS FOR
SULZER MODEL 2.5 FREQUENCY STANDARD
SERIAL NO. 256

Test	Condition	Length (Hours)	Drift Rate $\frac{\Delta f/F\ (pp\ 10^{11})}{hour}$	Standard Deviation (x 10^{11})
Static 1	normal	65	2.96	5.04
Static 2	side	49	2.38	6.18
Static 3	upside down	49	2.05	5.41
Static 4	side	48	1.79	4.17
Static 5	front	48	1.68	5.29
Static 6	back	48	1.53	11.35
Static 1	normal	68	1.47	9.30
Swing 1	5^o, 10^o, 30 sec.*	49	1.26	7.95
Swing 2	5^o, 10^o, 10 sec.	50	1.16	9.40
Swing 3	24^o, 30^o, 30 sec.	47	1.04	9.07
Swing 4	24^o, 30^o, 10 sec.	47	1.09	6.97
Swing 5	5^o, 10^o, 30 sec.	48	0.91	3.91
Swing 6	5^o, 10^o, 10 sec.	48	0.98	3.81
Swing 7	24^o, 30^o, 30 sec.	48	0.70	4.46
Swing 8	24^o, 30^o, 10 sec.	48	0.77	4.83
Static 1	normal	48	0.81	3.76

*5^o, 10^o, 30 sec. represents an asymmetric swing of 5^o off vertical in one direction and 10^o off vertical in the opposite direction with a period of 30 seconds.

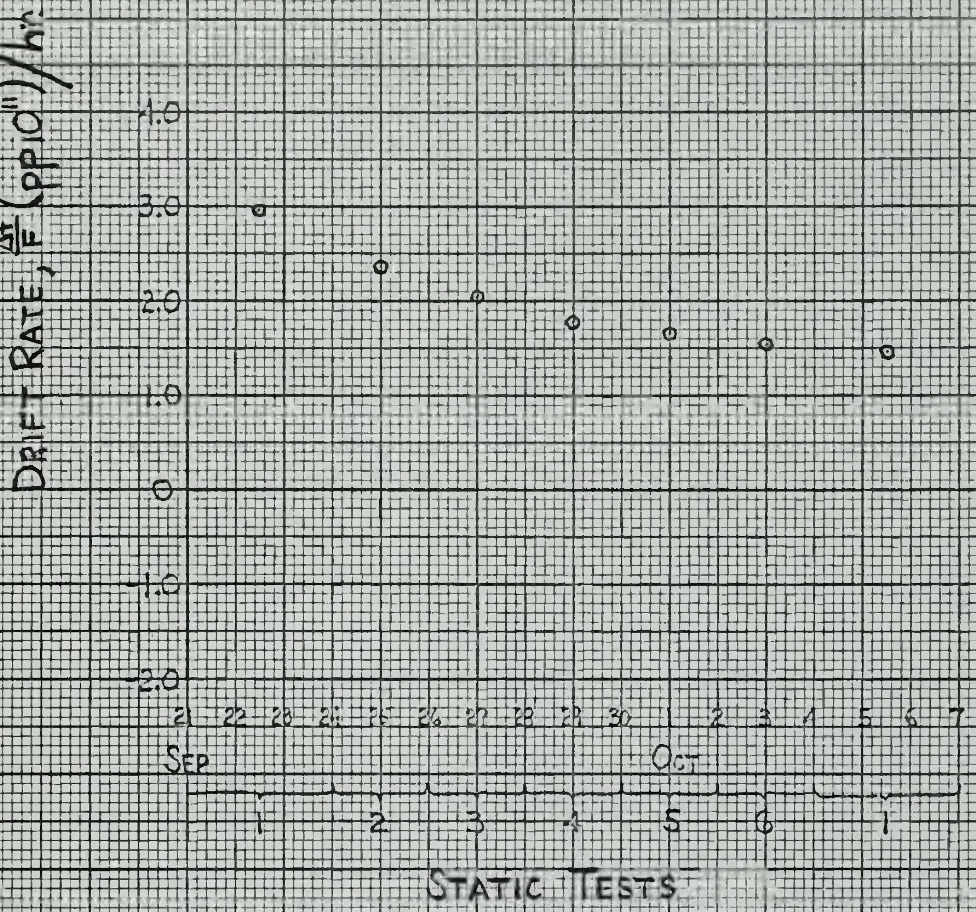

FIGURE 16

CHANGES IN DRIFT RATE
OF SULZER MODEL 2.5
DURING STATIC TESTS

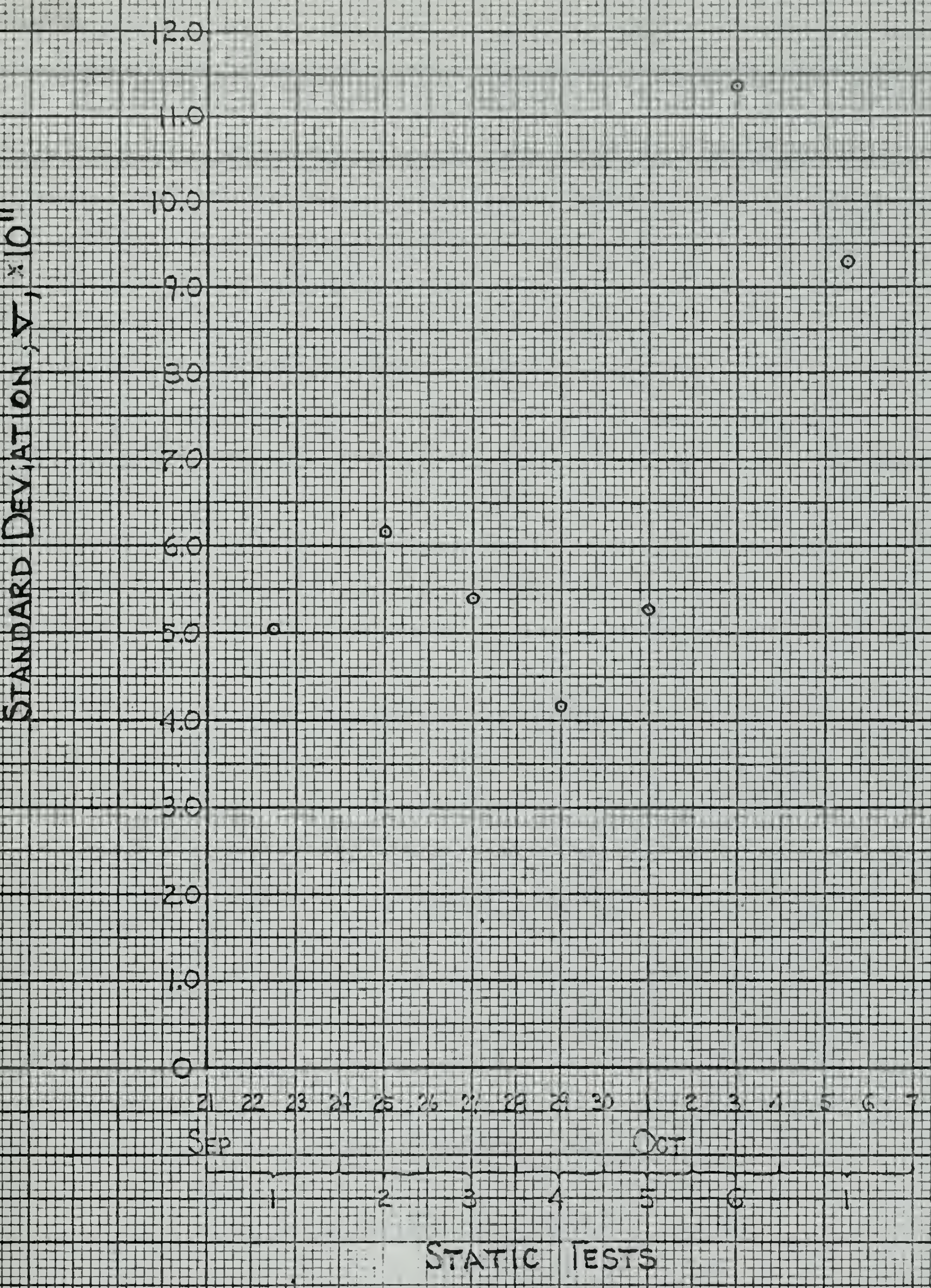

FIGURE 17

CHANGES IN STABILITY OF SULZER MODEL 2.5 DURING STATIC TESTS

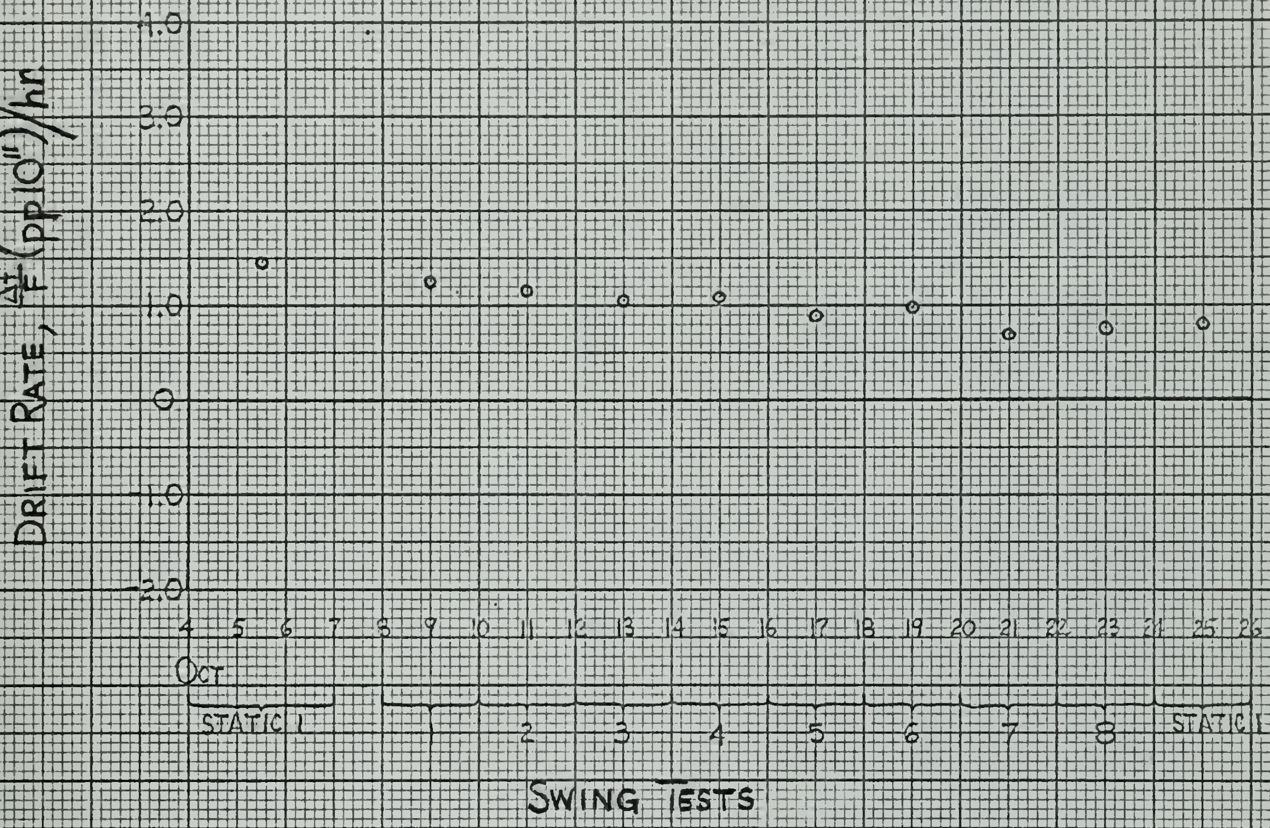

FIGURE 18

CHANGES IN DRIFT RATE
OF SULZER MODEL 2.5
DURING SWING TESTS

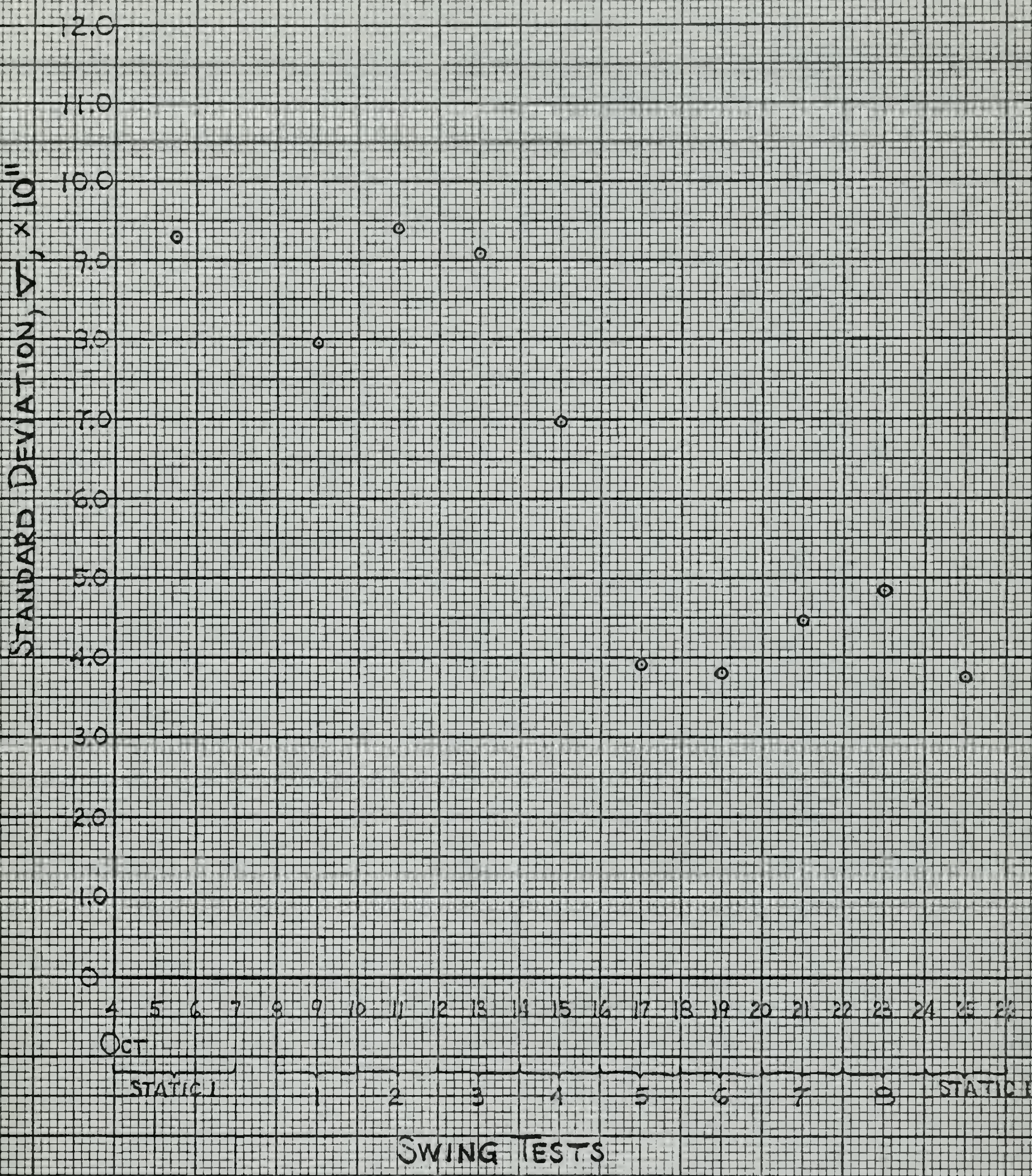

FIGURE 19

CHANGES IN STABILITY
OF SULZER MODEL 2.5
DURING SWING TESTS

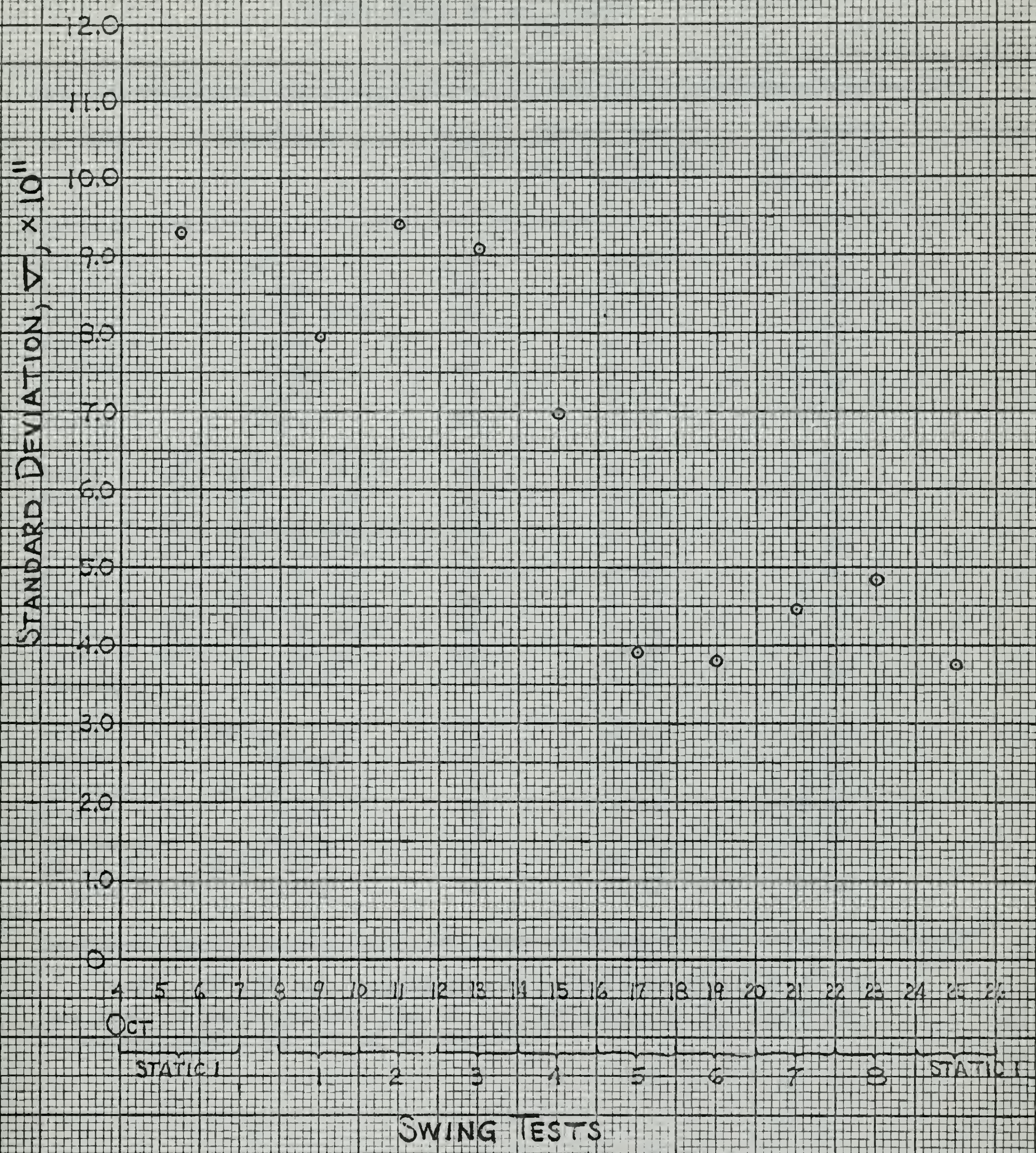

FIGURE 19

CHANGES IN STABILITY
OF SULZER MODEL 2.5
DURING SWING TESTS

TABLE VII

TEST RESULTS FOR
SULZER MODEL D5 OSCILLATOR
SERIAL NO. 25

Test	Condition	Length (hours)	Drift Rate $\frac{\Delta f/F \text{ (pp } 10^{11})}{\text{hour}}$	Standard Deviation ($\times 10^{11}$)
Static 1	normal	65	-4.14	8.46
Static 2	side	49	-3.61	7.28
Static 3	upside down	49	-3.13	6.17
Static 4	side	48	-2.81	7.10
Static 5	front	48	-2.51	5.93
Static 6	back	48	-2.26	8.22
Static 1	normal	68	-2.31	5.66
Swing 1	5^o, 10^o, 30 sec.*	49	-2.73	15.06
Swing 2	5^o, 10^o, 10 sec.	50	-2.25	12.63
Swing 3	24^o, 30^o, 30 sec.	47	-1.90	12.63
Swing 4	24^o, 30^o, 10 sec.	47	-1.47	4.28
Swing 5	5^o, 10^o, 30 sec.	48	-1.41	6.64
Swing 6	5^o, 10^o, 10 sec.	48	-1.42	9.28
Swing 7	24^o, 30^o, 30 sec.	48	-1.61	11.23
Swing 8	24^o, 30^o, 10 sec.	48	-0.68	9.30
Static 1	normal	48	-0.81	10.22
Vibrate 1	20 cps, 1 g	12	-5.02	3.92
Static 1	normal	12	-3.59	7.26
Vibrate 2	20 cps, 1 g	10	-2.42	9.64
Static 1	normal	18	-3.01	8.45
Static 1	normal	17	-1.01	7.99
Shock 1	0.3" fall	12	+0.71	9.11
Static 1	normal	60	-1.63	4.89

*5^o, 10^o, 30 sec. represents an asymmetric swing of 5^o off vertical in one direction and 10^o off vertical in the opposite direction with a period of 30 seconds.

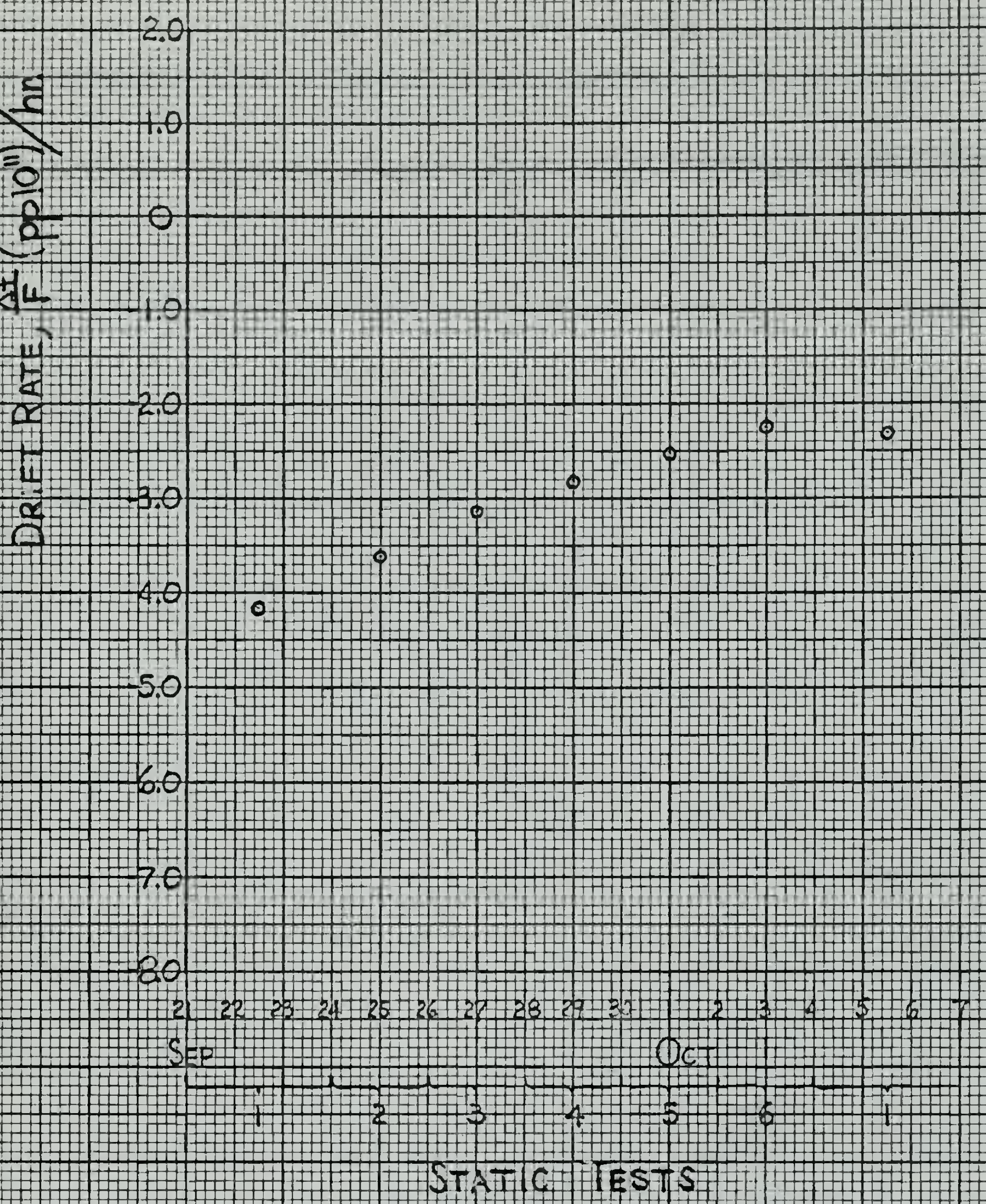

FIGURE 20

CHANGES IN DRIFT RATE
OF SULZER MODEL D5
SERIAL NO. 25
DURING STATIC TESTS

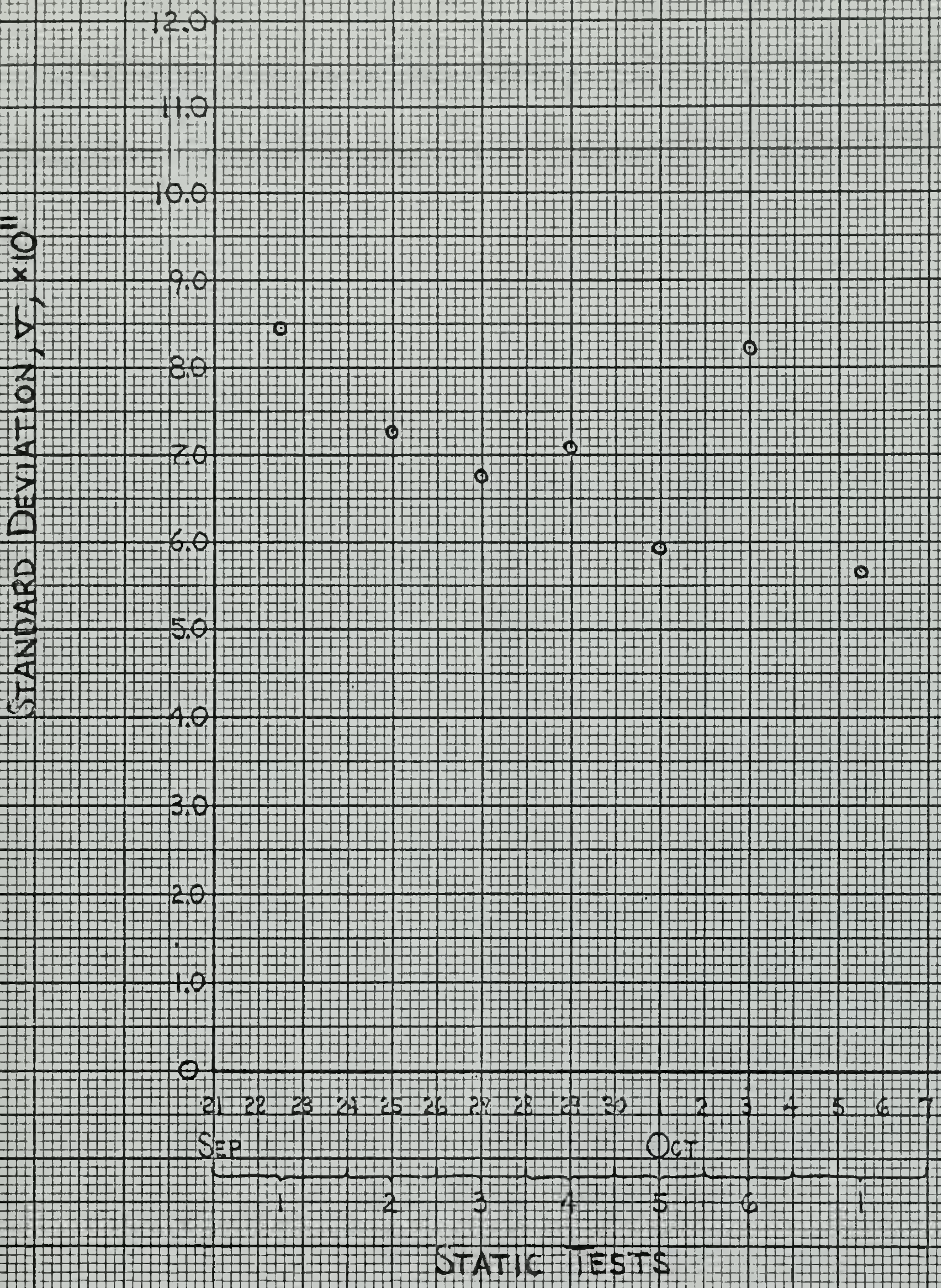

FIGURE 21

CHANGES IN STABILITY
OF SULZER MODEL D5
SERIAL NO. 25
DURING STATIC TESTS

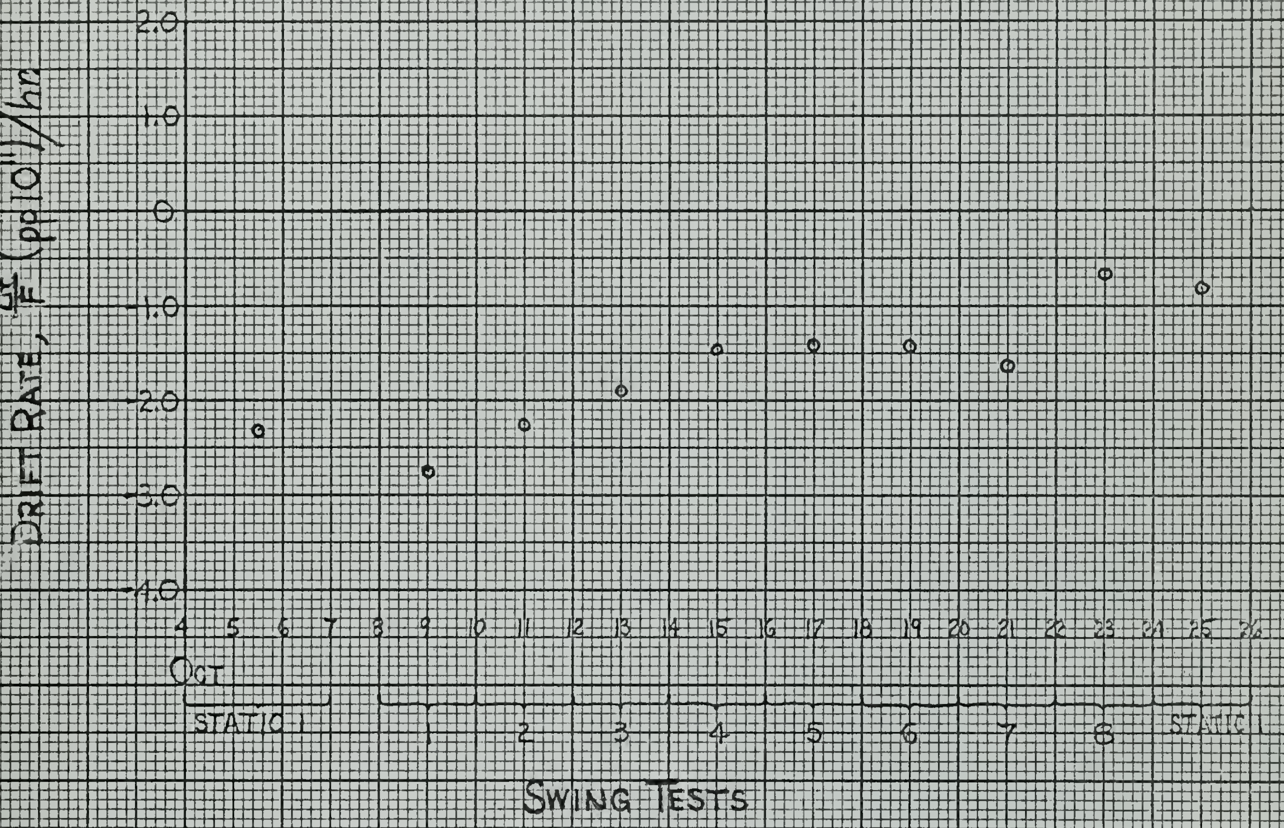

FIGURE 22

CHANGES IN DRIFT RATE
OF SULZER MODEL D5
SERIAL NO. 25
DURING SWING TESTS

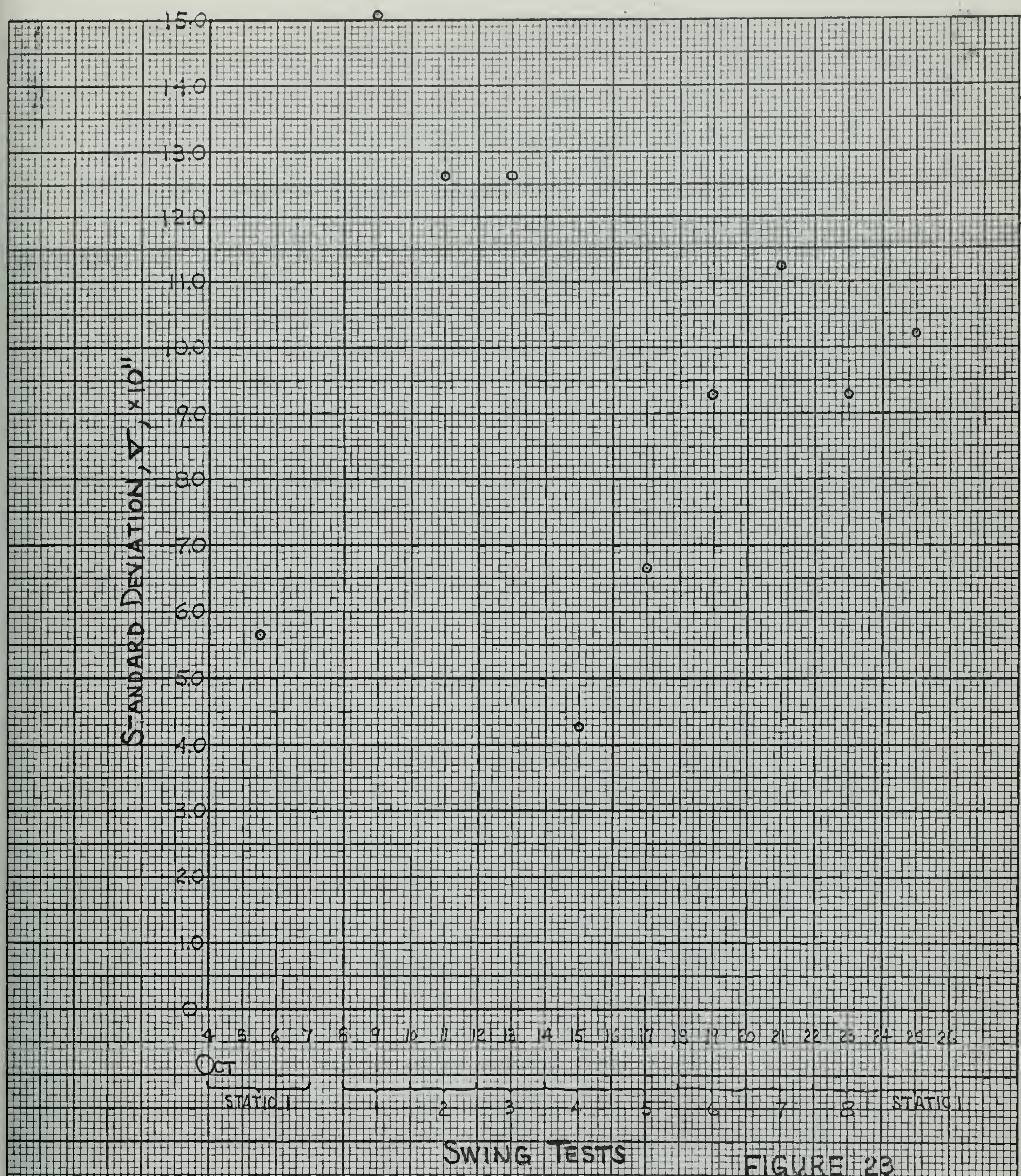

FIGURE 23

CHANGES IN STABILITY OF SULZER MODEL D5 SERIAL NO. 25 DURING SWING TESTS

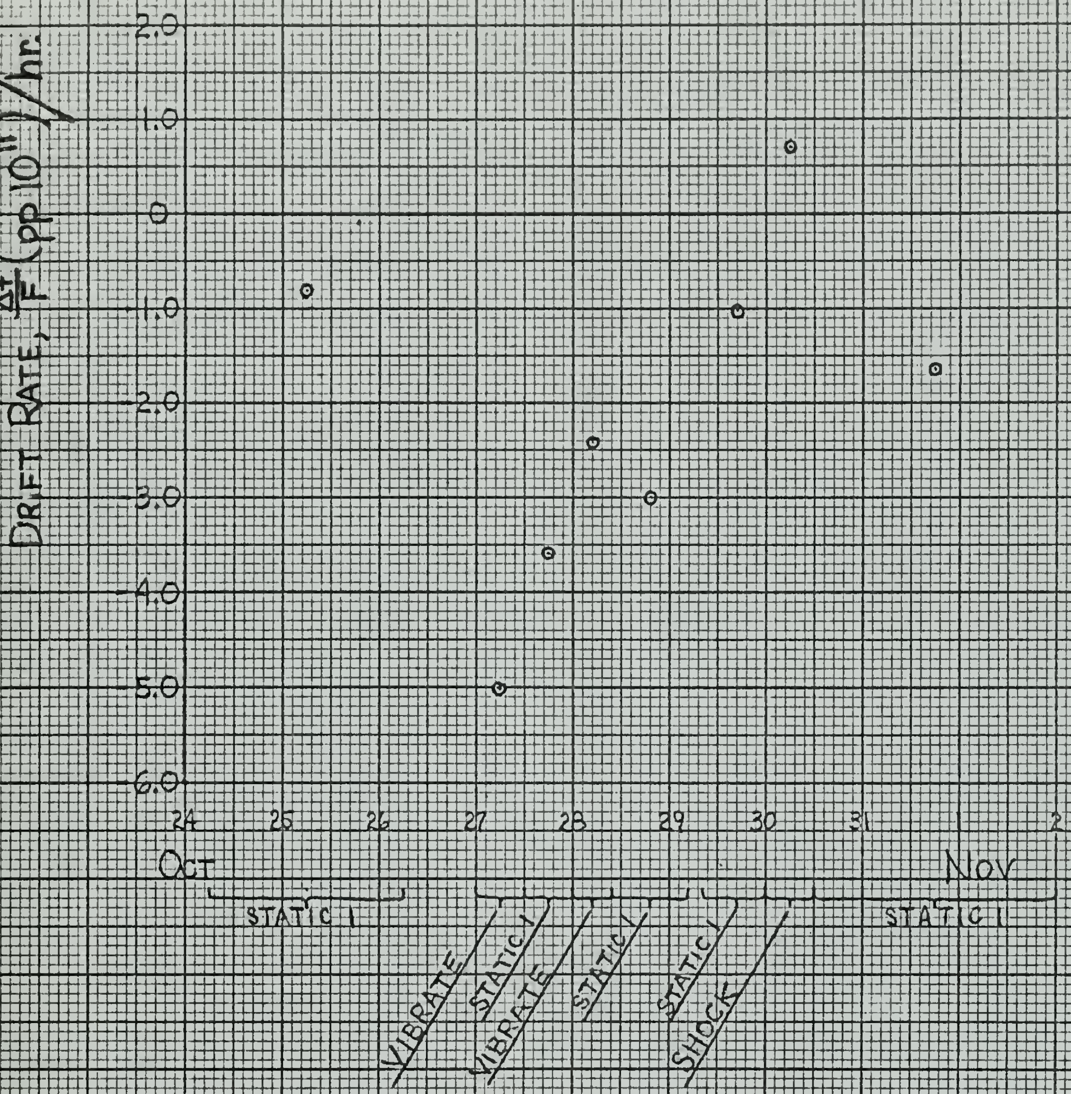

FIGURE 24

CHANGES IN DRIFT RATE OF
SULZER MODEL D5, SERIAL NO. 25
DURING VIBRATION AND SHOCK TESTS

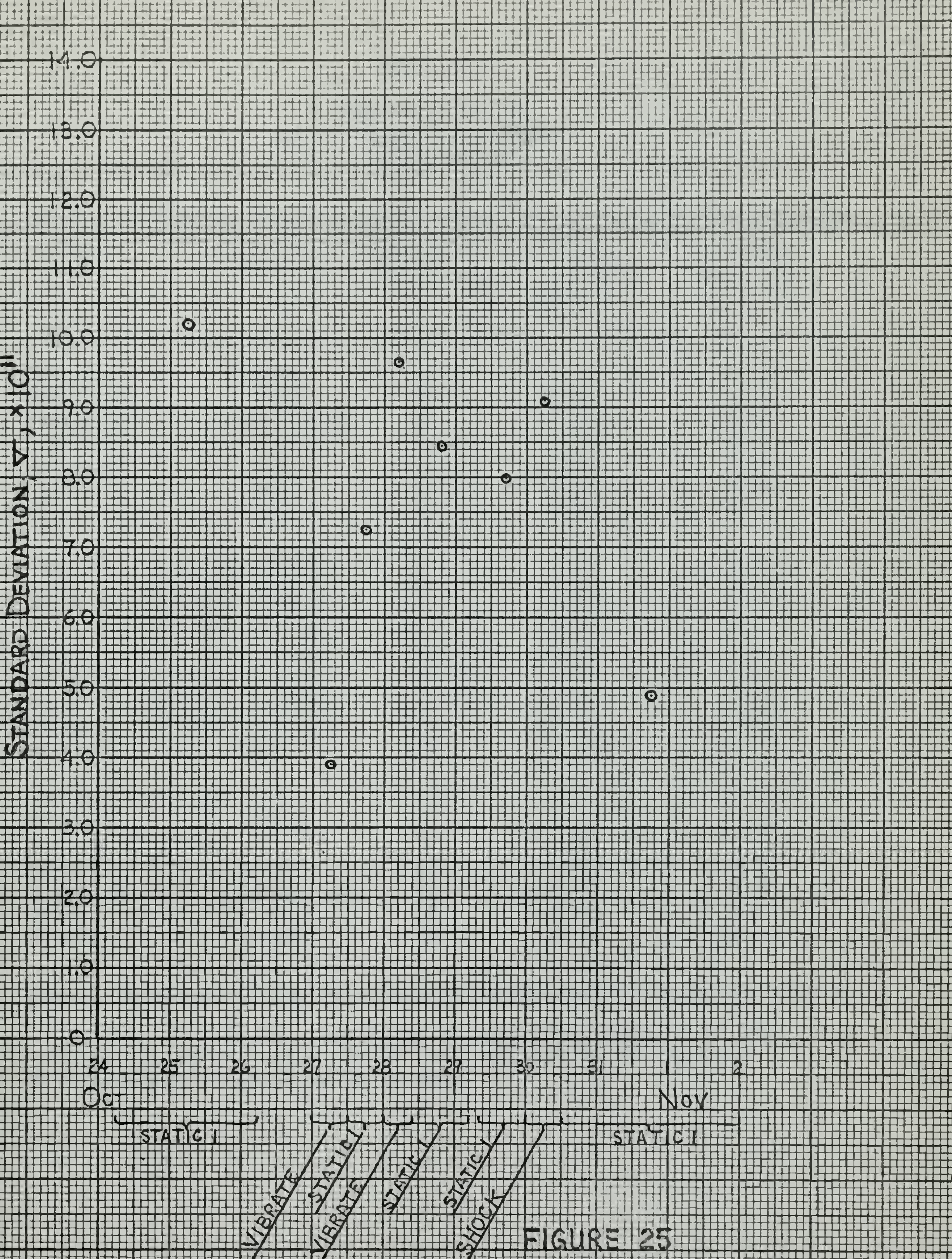

FIGURE 25

CHANGES IN STABILITY OF SULZER MODEL D5, SERIAL NO. 25 DURING VIBRATION AND SHOCK TESTS

TABLE VIII

TEST RESULTS FOR
SULZER MODEL D5 OSCILLATOR
SERIAL NO. 19

Test	Condition	Length (hours)	Drift Rate $\frac{\Delta f/F \text{ (pp } 10^{11})}{\text{hour}}$	Standard Deviation $(x\ 10^{11})$
Static 1	normal	65	-6.29	8.46
Static 2	side	49	-4.82	8.33
Static 3	upside down	49	-3.96	8.36
Static 4	side	48	-3.52	8.32
Static 5	front	48	-3.02	8.86
Static 6	back	48	-3.28	8.98
Static 1	normal	68	-2.86	6.32
Swing 1	5^o, 10^o, 30 sec.*	49	-3.31	8.75
Swing 2	5^o, 10^o, 10 sec.	50	-2.68	7.68
Swing 3	24^o, 30^o, 30 sec.	47	-2.46	4.74
Swing 4	24^o, 30^o, 10 sec.	47	-2.22	4.12
Swing 5	5^o, 10^o, 30 sec.	48	-2.03	6.06
Swing 6	5^o, 10^o, 10 sec.	48	-2.12	4.67
Swing 7	24^o, 30^o, 30 sec.	48	-2.12	5.88
Swing 8	24^o, 30^o, 10 sec.	48	-1.77	9.96
Static 1	normal	48	-1.64	8.22
Vibrate 1	20 cps, 1 g	12	-4.63	9.55
Static 1	normal	12	-3.11	4.25
Vibrate 2	20 cps, 1 g	10	-3.81	5.10
Static 1	normal	18	-3.03	9.52
Static 1	normal	17	-1.69	5.86
Shock 1	0.3" fall	12	-2.36	8.45
Static 1	normal	60	-2.19	10.06

*5^o, 10^o, 30 sec. represents an asymmetric swing of 5^o off vertical in one direction and 10^o off vertical in the opposite direction with a period of 30 seconds.

[illegible]

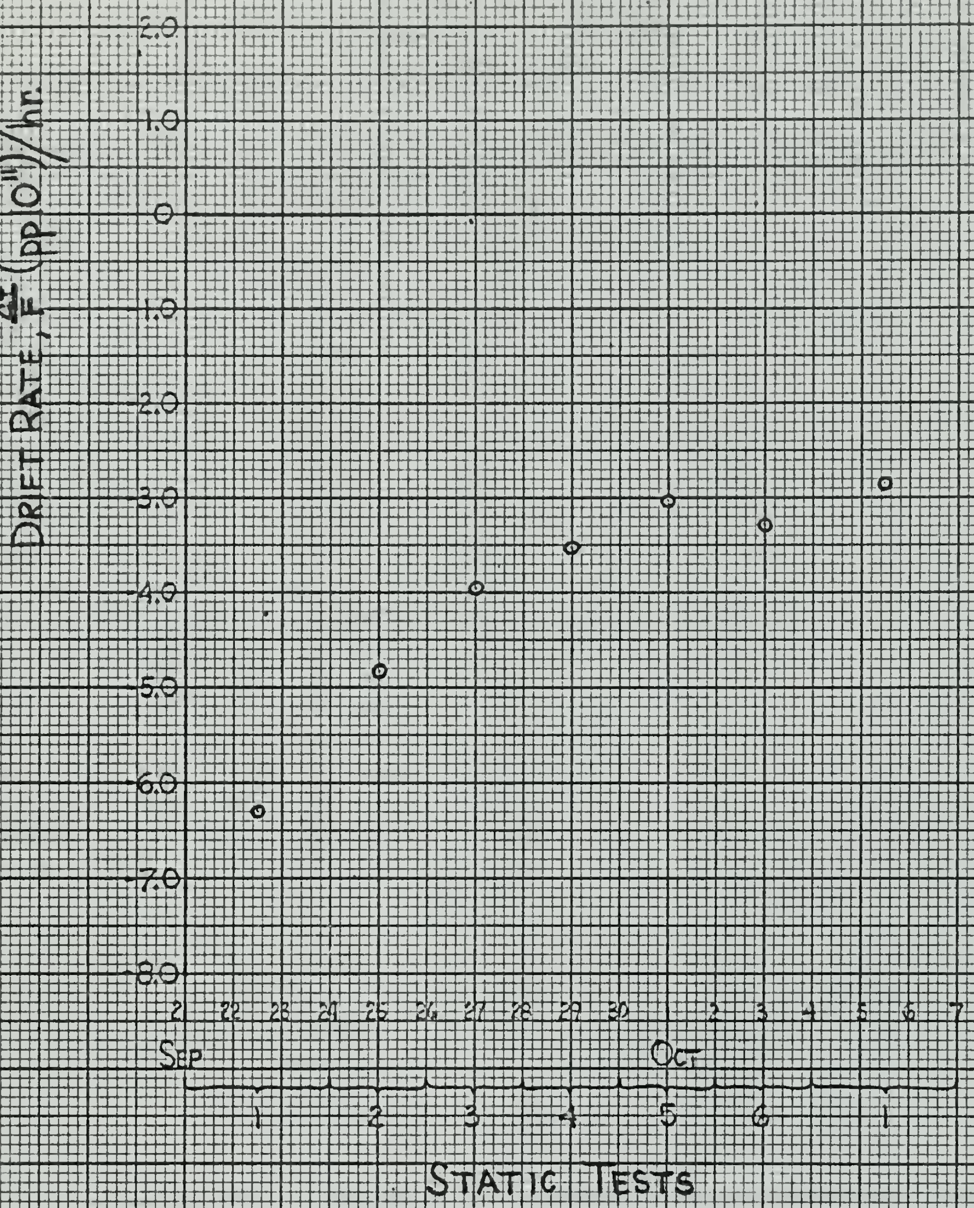

FIGURE 26

CHANGES IN DRIFT RATE
OF SULZER MODEL D5
SERIAL NO. 19
DURING STATIC TESTS

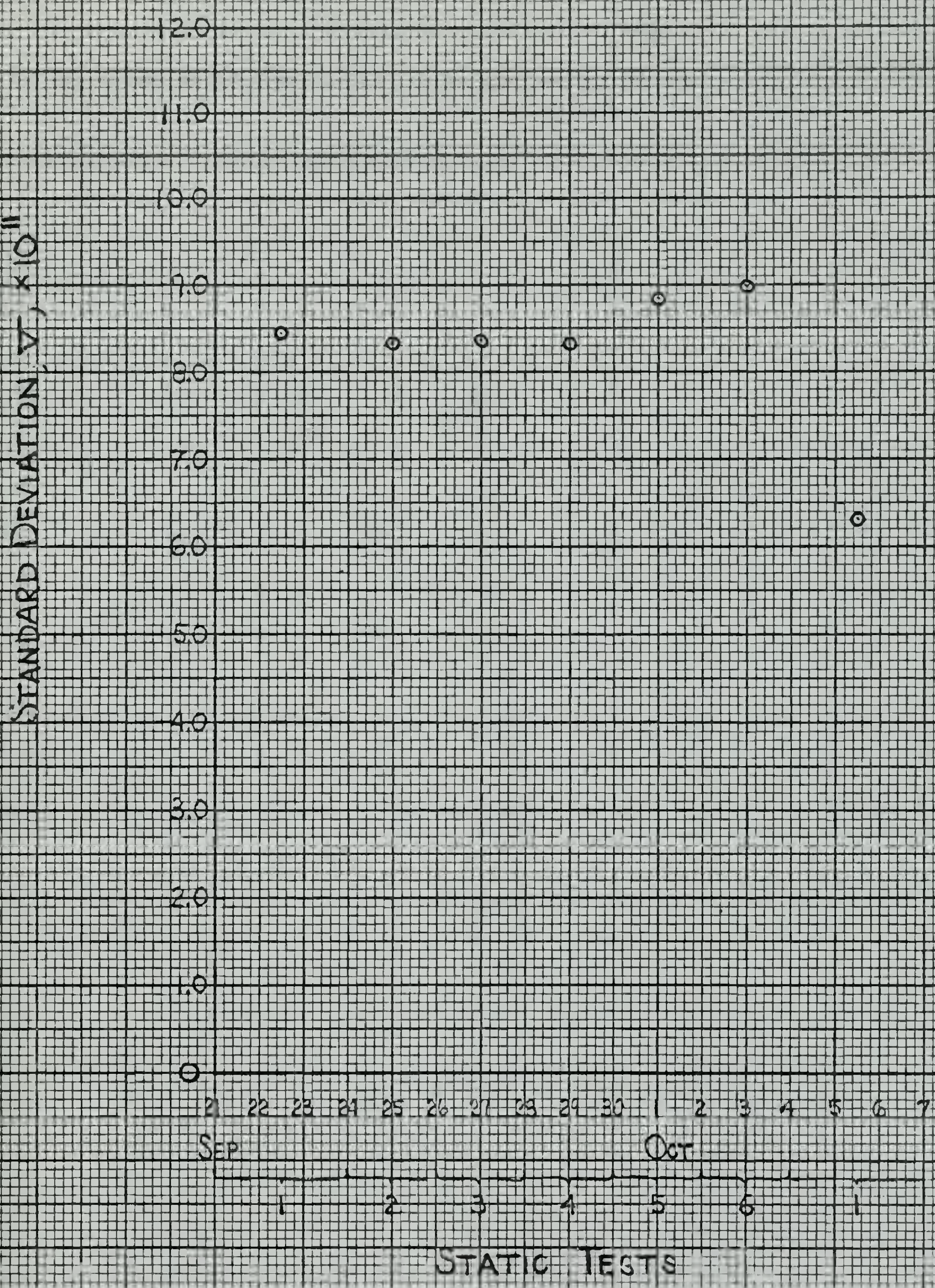

FIGURE 27

CHANGES IN STABILITY
OF SULZER MODEL D5
SERIAL NO. 19
DURING STATIC TESTS

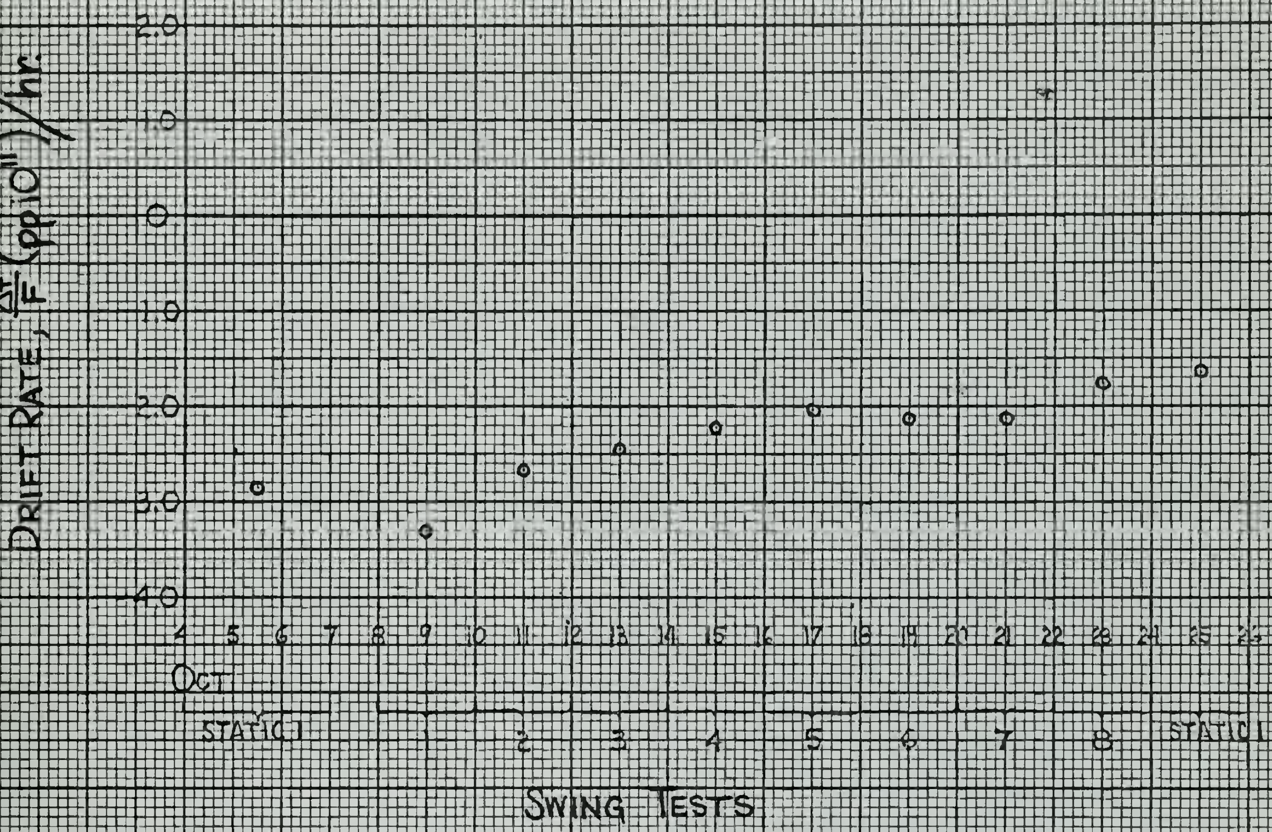

FIGURE 28

CHANGES IN DRIFT RATE
OF SULZER MODEL D5
SERIAL NO. 19
DURING SWING TESTS

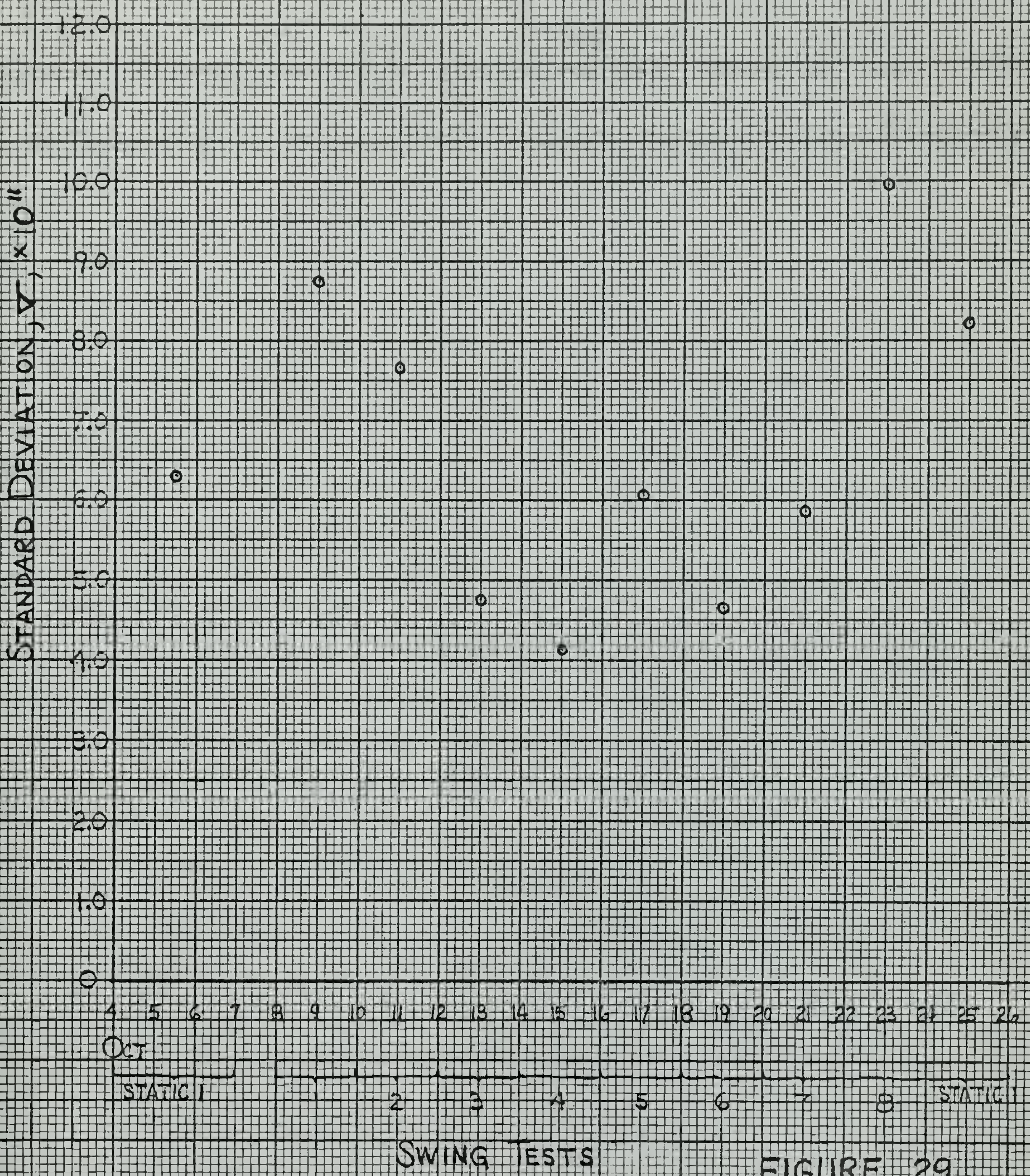

FIGURE 29

CHANGES IN STABILITY OF SULZER MODEL D5 SERIAL NO. 19 DURING SWING TESTS

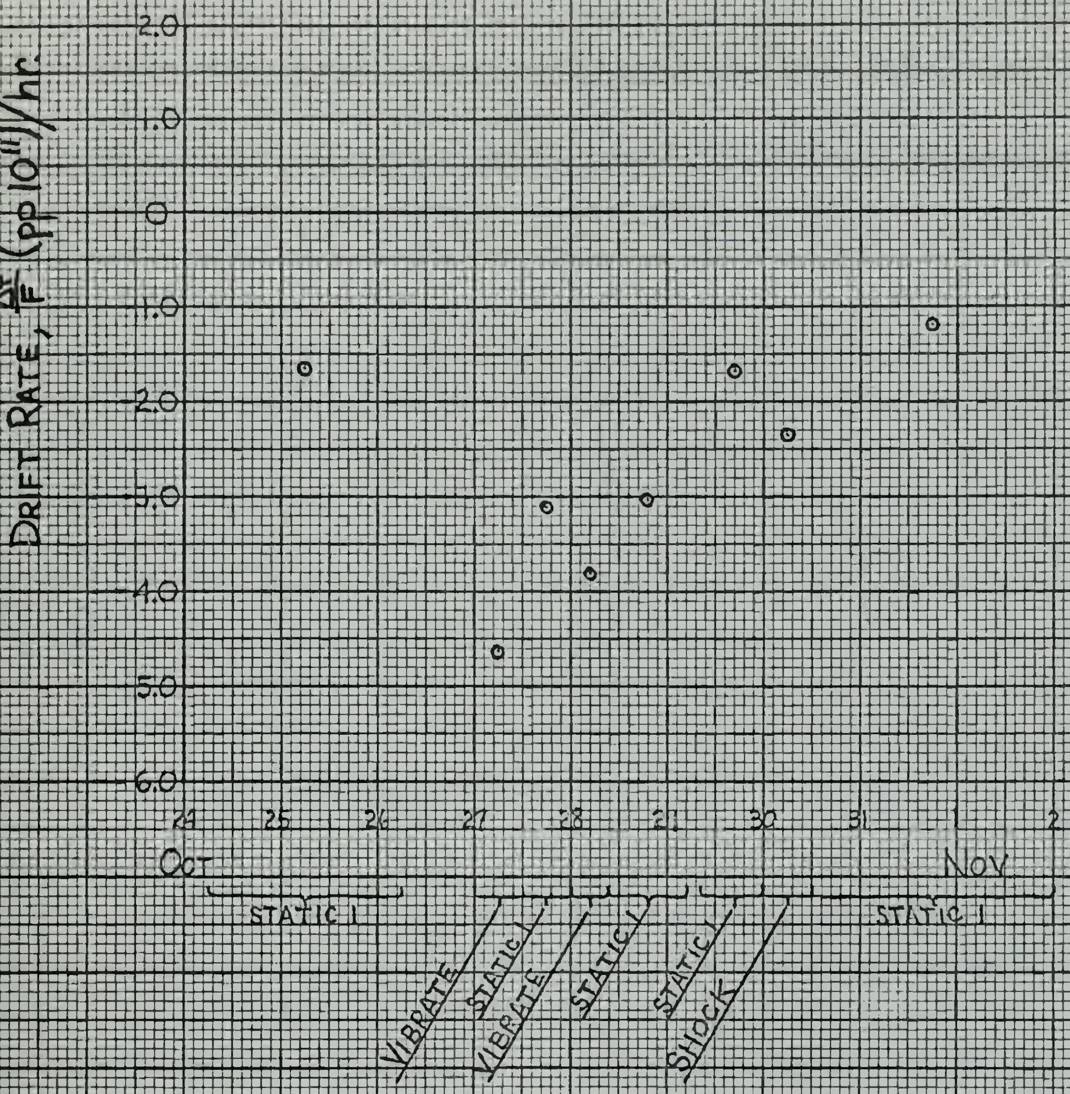

FIGURE 30

CHANGES IN DRIFT RATE OF SULZER MODEL D5, SERIAL NO. 19 DURING VIBRATION AND SHOCK TESTS

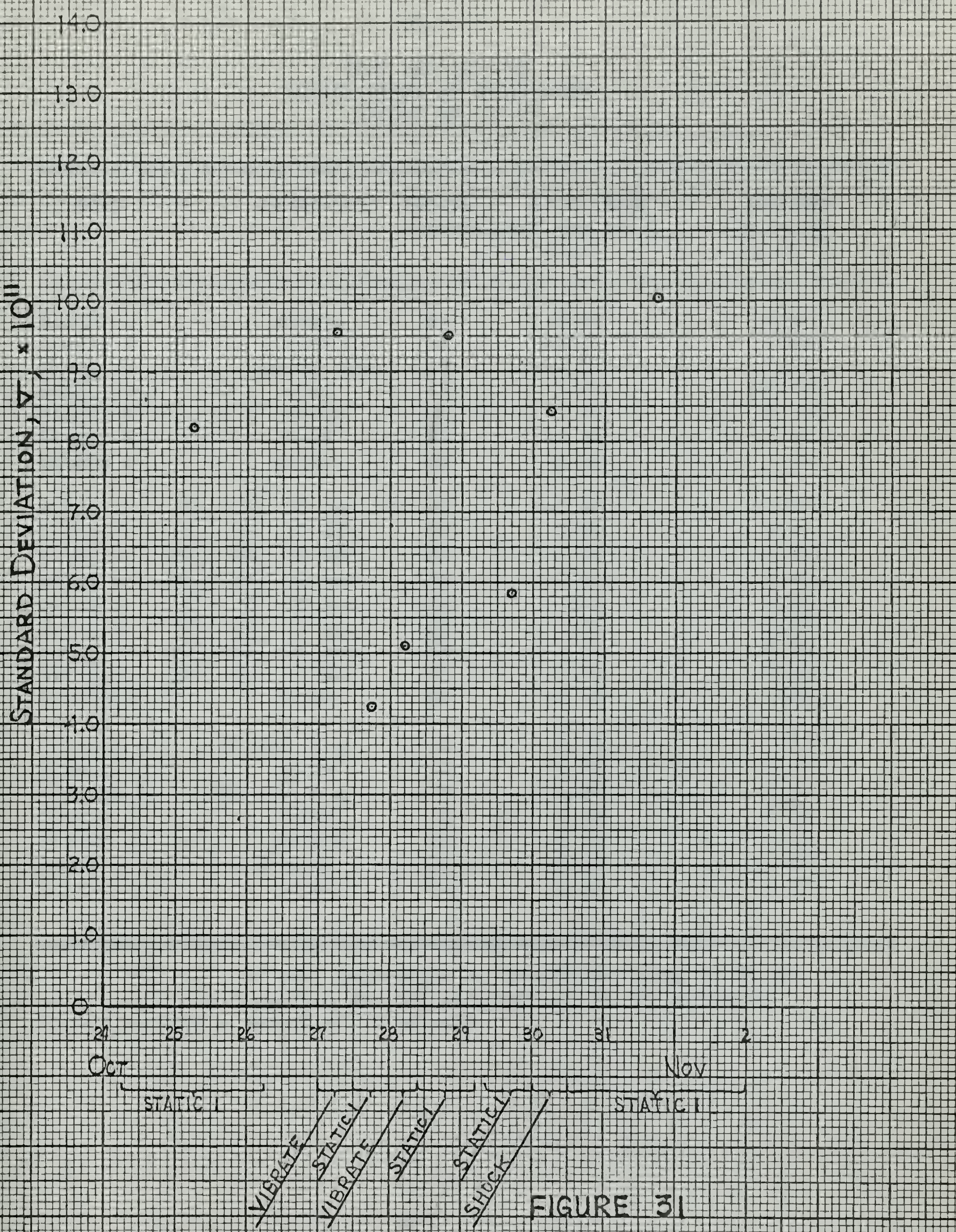

FIGURE 31

CHANGES IN STABILITY OF SULZER MODEL D5, SERIAL NO. 19 DURING VIBRATION AND SHOCK TESTS

TABLE IX

TEST RESULTS FOR
SULZER MODEL D5 OSCILLATOR
SERIAL NO. 22

Test	Condition	Length (hours)	Drift Rate $\frac{\Delta f/F \ (\text{pp } 10^{11})}{\text{hour}}$	Standard Deviation ($\times 10^{11}$)
Static 1	normal	65	-6.68	4.97
Static 2	side	49	-5.14	7.44
Static 3	upside down	49	-4.31	6.31
Static 4	side	48	-4.26	10.12
Static 5	front	48	-2.90	9.77
Static 6	back	48	-2.64	7.67
Static 1	normal	68	-2.26	8.64
Swing 1	5°, 10°, 30 sec. *	49	-2.41	7.85
Swing 2	5°, 10°, 10 sec.	50	-2.10	5.20
Swing 3	24°, 30°, 30 sec.	47	-1.76	4.09
Swing 4	24°, 30°, 10 sec.	47	-1.54	4.08
Swing 5	5°, 10°, 30 sec.	48	-1.42	4.47
Swing 6	5°, 10°, 10 sec.	48	-1.32	3.07
Swing 7	24°, 30°, 30 sec.	48	-1.39	3.09
Swing 8	24°, 30°, 10 sec.	48	-1.08	4.65
Static 1	normal	48	-0.95	5.00
Vibrate 1	20 cps, 1 g	12	-4.50	7.46
Static 1	normal	12	-2.74	2.18
Vibrate 2	20 cps, 1 g	10	-2.80	2.56
Static 1	normal	18	-1.99	4.26
Static 1	normal	17	-0.55	3.32
Shock 1	0.3" fall	12	-0.02	7.39
Static 1	normal	60	-1.14	4.37

*5°, 10°, 30 sec. represents an asymmetric swing of 5° off vertical in one direction and 10° off vertical in the opposite direction with a period of 30 seconds.

[illegible]

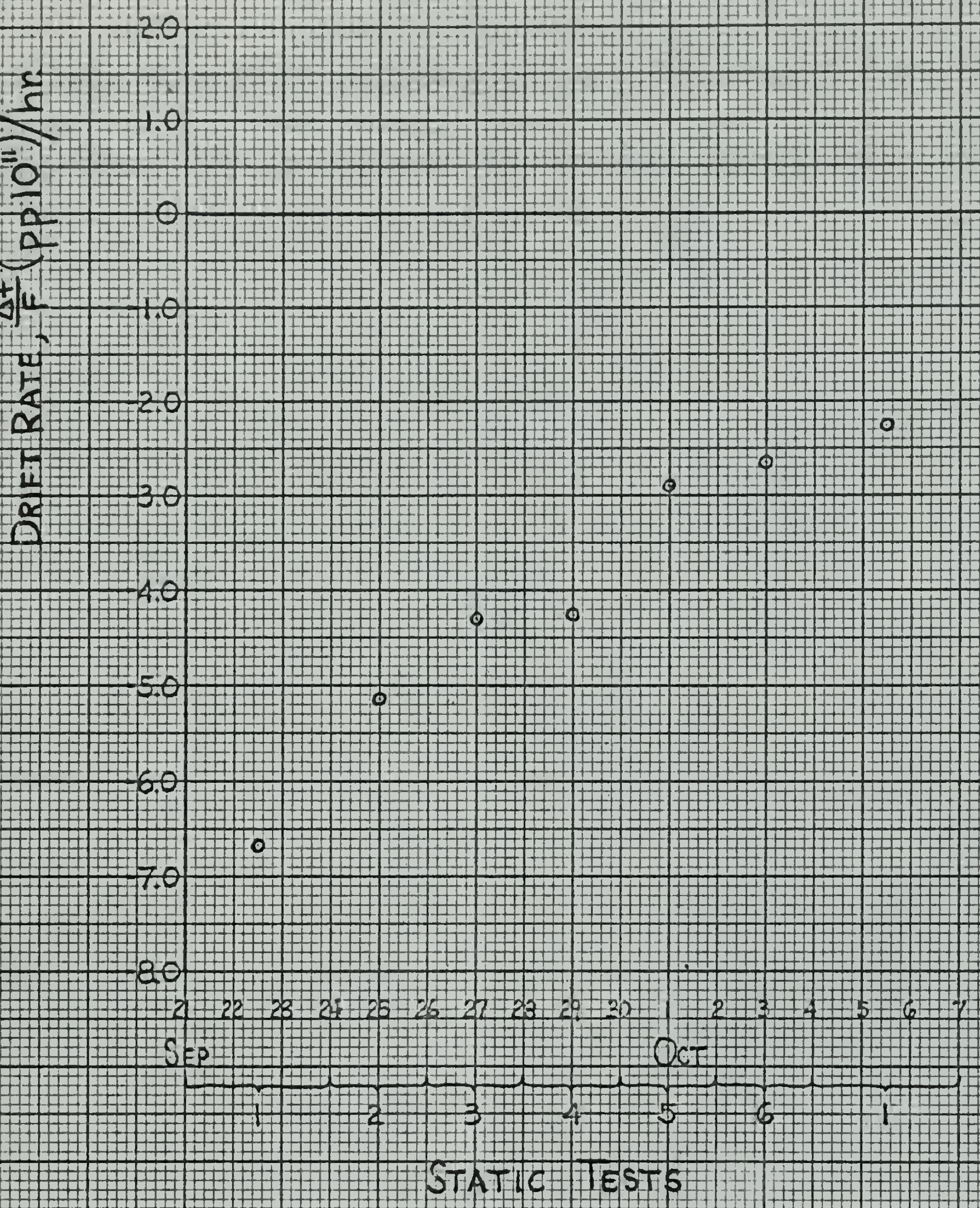

FIGURE 32

CHANGES IN DRIFT RATE
OF SULZER MODEL D5
SERIAL NO. 22
DURING STATIC TESTS

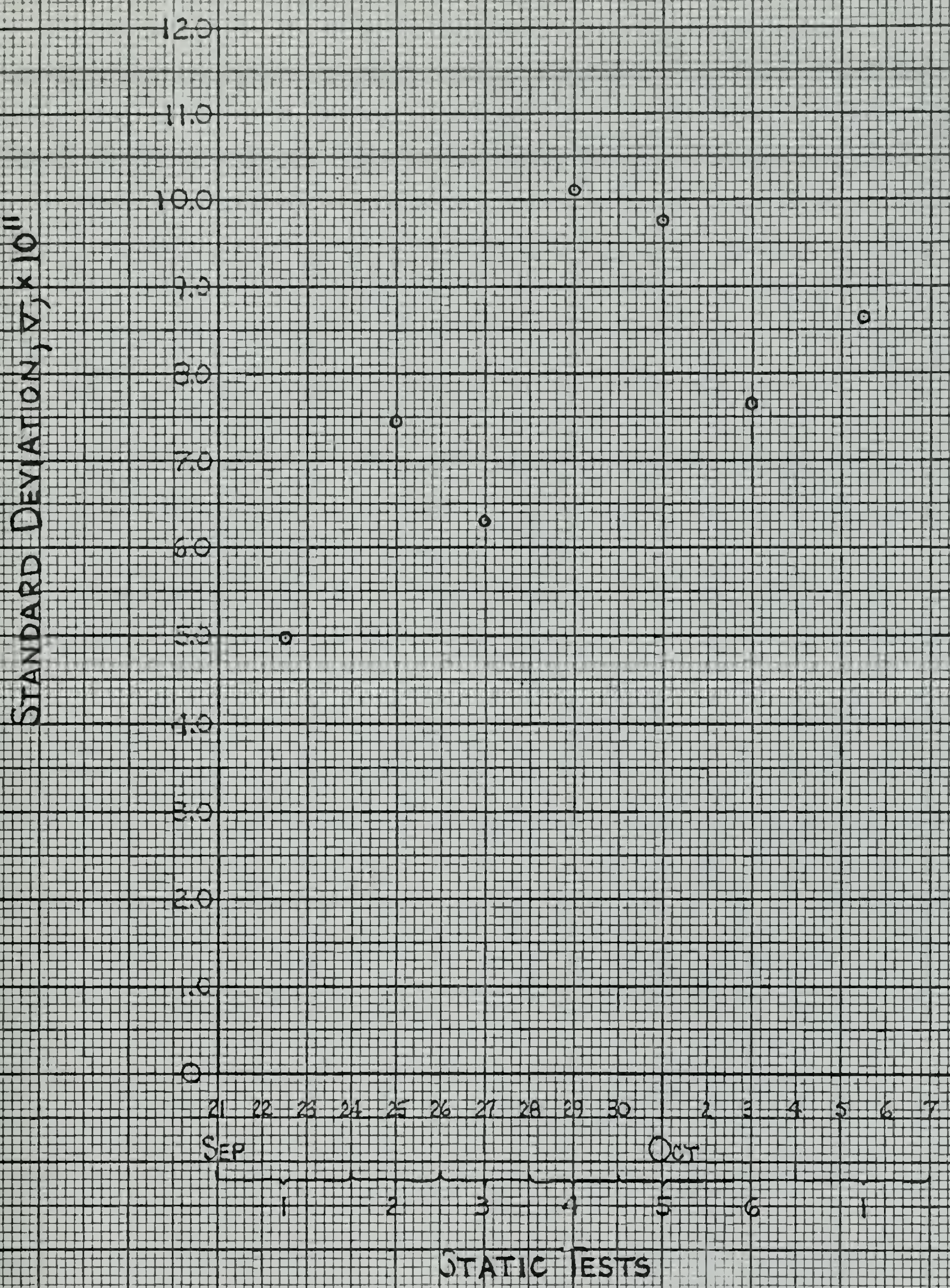

FIGURE 33

CHANGES IN STABILITY
OF SULZER MODEL D5
SERIAL NO. 22
DURING STATIC TESTS

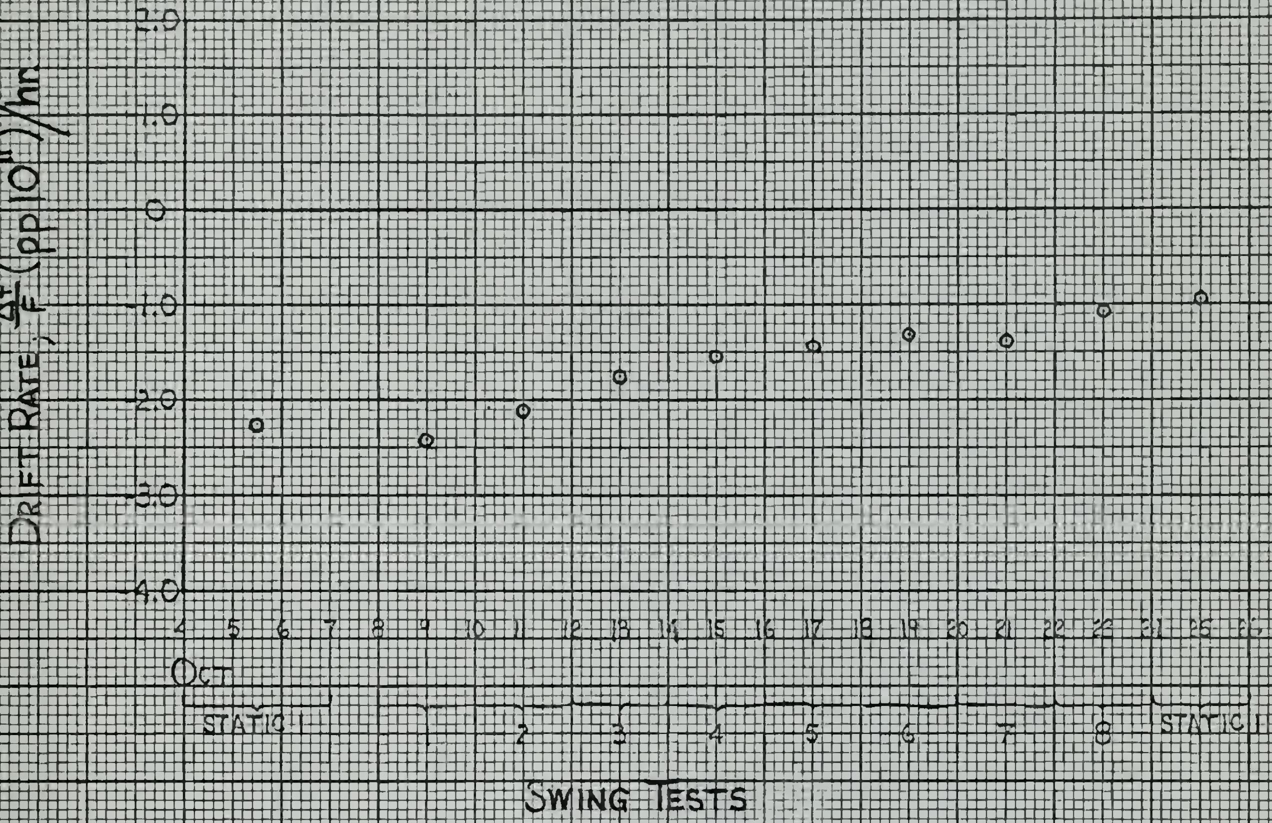

FIGURE 34

CHANGES IN DRIFT RATE
OF SULZER MODEL D5
SERIAL NO. 22
DURING SWING TESTS

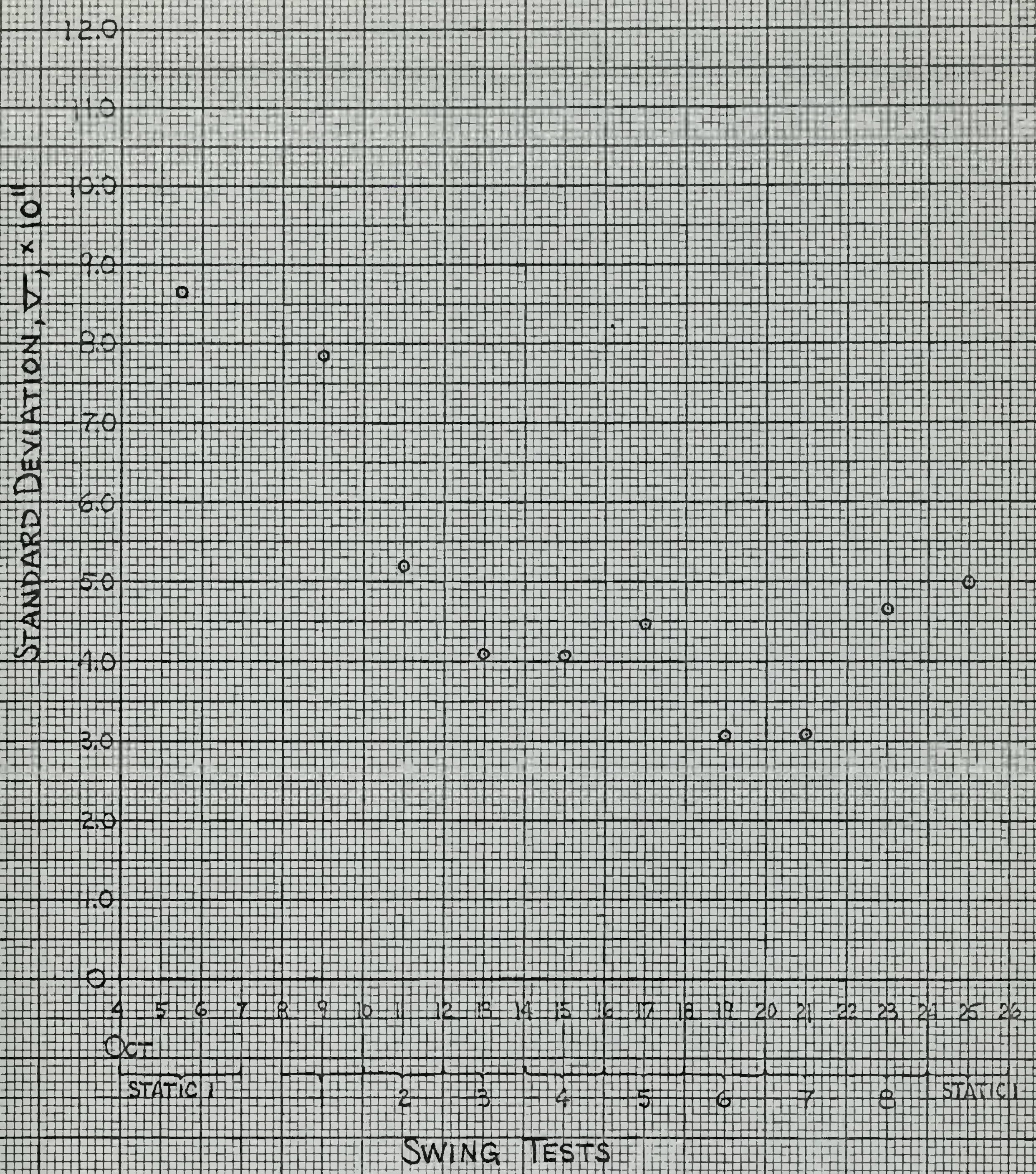

FIGURE 35

CHANGES IN STABILITY
OF SULZER MODEL D5
SERIAL NO. 22
DURING SWING TESTS

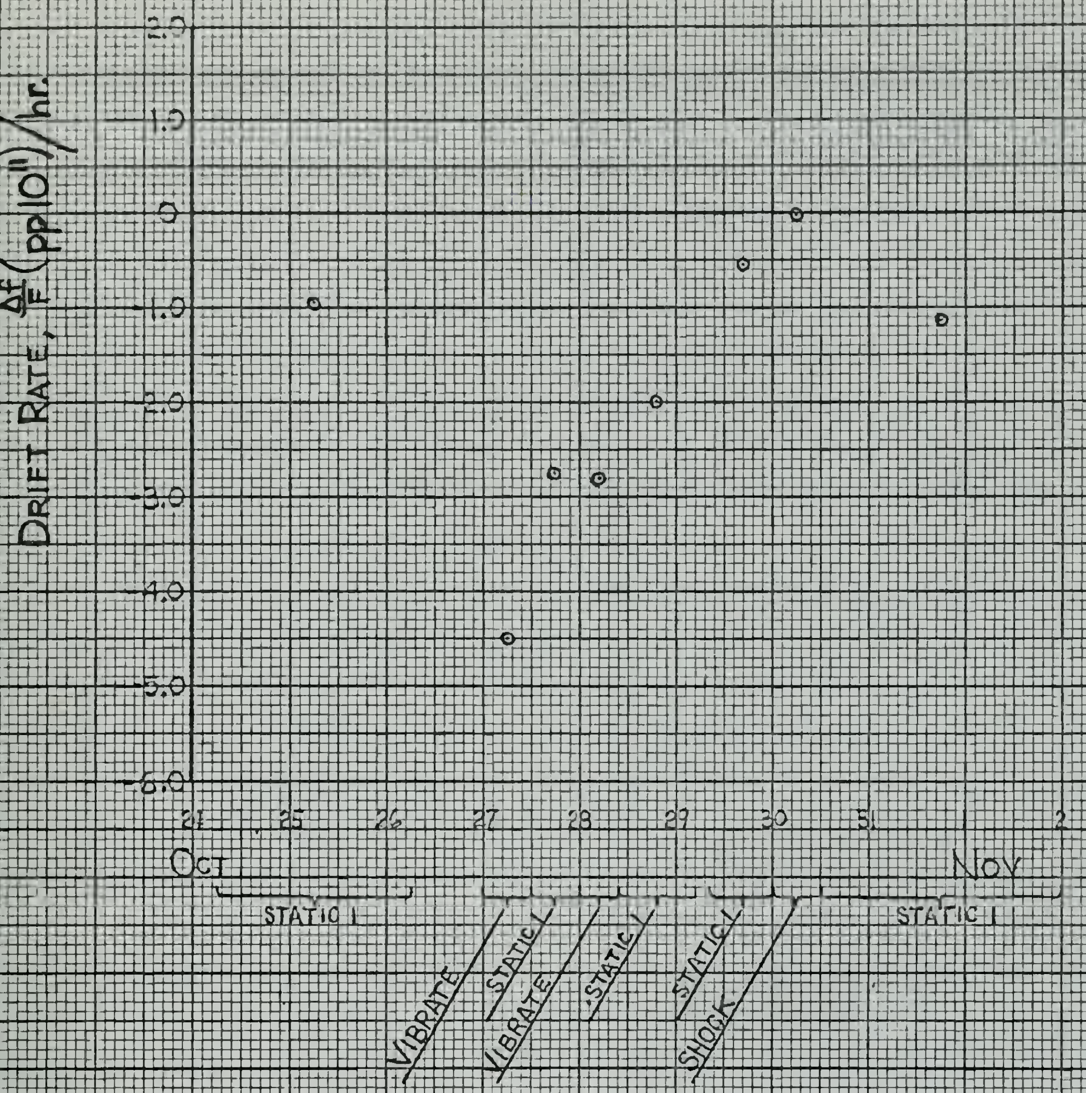

FIGURE 36

CHANGES IN DRIFT RATE OF SULZER MODEL D5, SERIAL NO. 22 DURING VIBRATION AND SHOCK TESTS

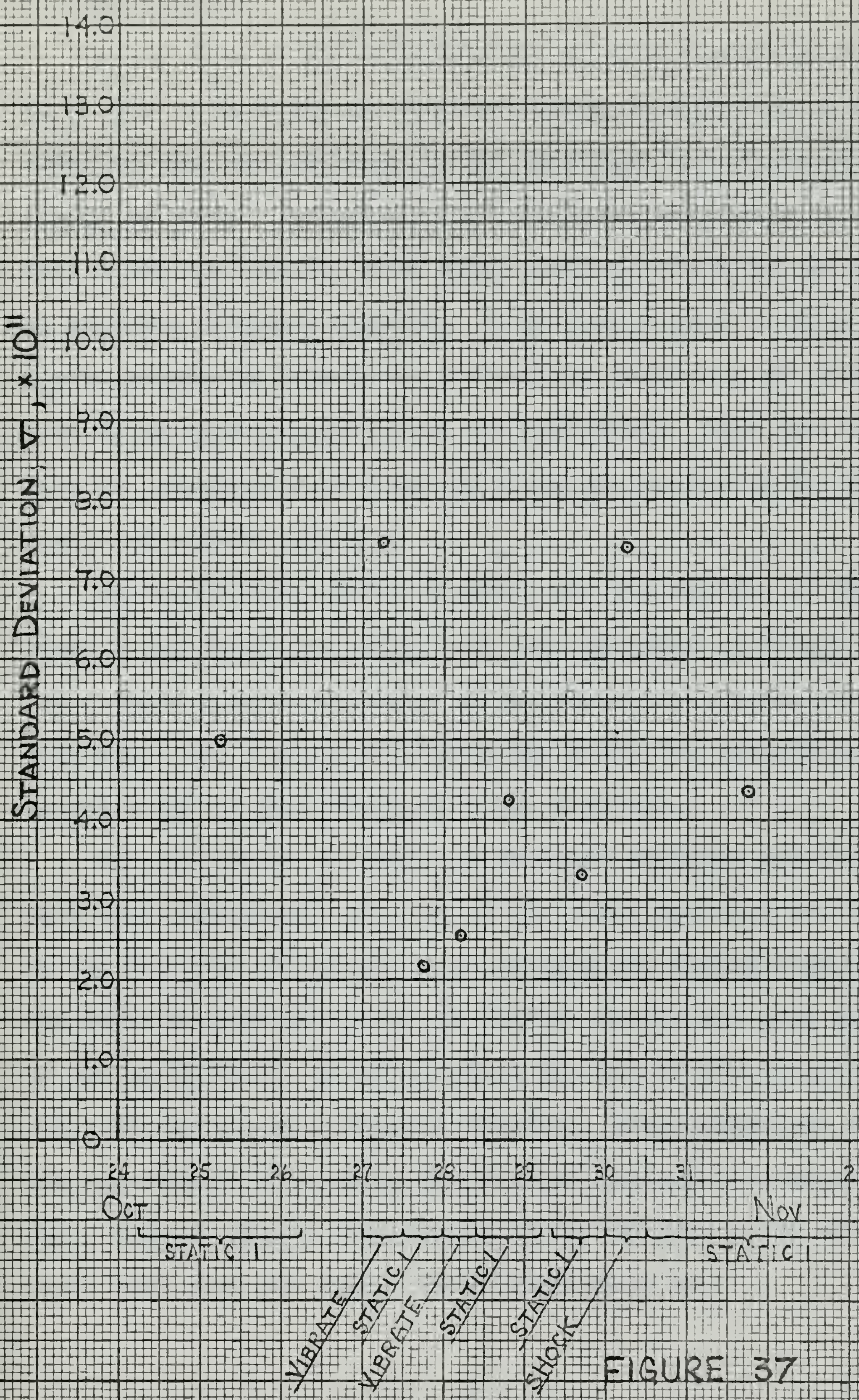

FIGURE 37

CHANGES IN STABILITY OF SULZER MODEL D5, SERIAL NO. 22 DURING VIBRATION AND SHOCK TESTS

6. Observations.

At the onset of the investigation, the investigator had hoped to be able to correlate any observed changes in drift rate or frequency stability with the conditions of the particular test during which the change was noted. A seemingly ideal situation was present with the four Sulzer oscillators, three being identical models and the fourth an excellent frequency standard. It had been planned to obtain additional information from Sulzer Laboratories concerning the orientation of the crystal plane within the oscillators. With this information the investigator had hoped to relate the results of the static tests with crystal position.

The manufacturer stated, however, that the position of the crystal plane is not fixed, but varies with each individual oscillator. Since the only remaining method of determining the crystal orientation would have required disturbing the double-oven assemblies, this second aspect of the investigation was abandoned.

The correlation of changes in frequency stability and drift rates with test conditions in the case of the Sulzer equipment was hampered by the fact that the limited time available for testing required that the tests be conducted during the initial warm-up and aging period of the oscillators. As the equipment was new, no data record was available for use as a behavior reference. These conditions prevented the investigator from making the detailed conclusions originally hoped for. Instead, general observations of the behavior of the oscillators while under test were made. These observations are:

[illegible]

[illegible]

[illegible]

[illegible]

Western Electric Frequency Standard 0-76A/U

Static Tests. Drift rates varied between 0.04 (pp 10^9) per hour and 1.49 (pp 10^9) per hour, with the lowest value occurring while the oscillator was in the normal position. However, each time the oscillator was in this position, a different drift rate was observed (0.11, 0.10, 0.04). During a portion of the Static Five test with the oscillator tipped forward on its face the drift rate was 0.05 (pp 10^9)/hr.

Stability (standard deviation) varied from 0.35×10^{-9} to 1.12×10^{-9} with the lowest value occurring while the unit was in a normal position. However, as in the case of the drift rates, each time the oscillator was returned to its normal position, a different value was observed (0.35, 0.32, 0.57). Once again there were instances where the stability while the oscillator was in some position other than normal was better than that observed for some of the normal position test periods.

The maximum values of drift rate and standard deviation occurred during the recovery periods as discussed in Section 5.

Swing Tests. The drift rate was certainly affected by the swinging motion although during the test period from 12 to 14 September while the oscillator was in the Static One position the drift rate was almost as great as the largest observed during swinging. The rates varied from 0.133 (pp 10^9)/hr. to -0.037 (pp 10^9)/hr.

Values of standard deviation were generally greater during swinging than while at rest, indicating poorer stability under these conditions.

Sulzer Model 2.5 Frequency Standard

Static Tests. The drift rate gradually decreased as the crystal aged and no apparent effects of static position were observed.

Stability varied between 4.2×10^{-11} and 11.4×10^{-11} with the greatest value observed during the Static Six test, while the unit was tipped on its back.

Swing Tests. The drift rate continued to decrease gradually with further aging of the crystal. In three out of four instances, however, the drift rate increased slightly when the swing frequency was increased.

Stability improved as the swing tests progressed, with values of the standard deviation decreasing from 9.3×10^{-11} to 3.8×10^{-11}. In three out of four instances, however, the standard deviation increased when the amplitude of the swing was increased.

Sulzer Model D5 Oscillators

Static Tests. As in the case of the Sulzer frequency standard, the drift rate for each of the three Model D5 oscillators gradually decreased during the aging period.

Stabilities varied between 5×10^{-11} and 10×10^{-11} with no common behavior pattern evident. One oscillator exhibited a downward trend, one an upward trend, and one remained fairly constant.

Swing Tests. The drift rates generally decreased during the swinging tests as aging continued.

Stabilities varied from 3×10^{-11} to 15×10^{-11}. The lowest values of standard deviation for each oscillator were obtained during one or another of the swing tests and not during a static period. In three out of four instances when the swing frequency was increased, the stability of various oscillators improved. The exceptional cases, however, did not occur simultaneously.

The stability of two of the oscillators, serial no. 19 and serial no. 22, improved in three out of four instances when the amplitude of the swing was increased.

Vibration and Shock Tests. All drift rates were increased by three or four parts per 10^{11} per hour during the initial vibration test.

Standard deviation varied between 2.2×10^{-11} and 10.1×10^{-11}. All standard deviations were increased during the shock test; the amounts of increase varied from one to four parts per 10^{11}.

In conclusion, the drift rate and frequency stability of the frequency standards were apparently affected to a small degree by swinging motion, although this motion had no definite effect on the Sulzer Model D5 oscillators. The D5 oscillators were affected slightly by shock and vibration. In only a few cases, however, such as the change in stability during the shock test, or the change in drift rate during the initial vibration test, did all three Model D5

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

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[illegible]

oscillators respond in a similar manner. Generally, opposite reactions occurred, i.e., during a given test period, drift rates of two oscillators would increase while the third decreased, or the stabilities of a different pair of oscillators would decrease while the third increased or remained constant.

In spite of the lack of positive correlation of changes in drift rate and stability with conditions of position and motion, the results of the investigation were fruitful in that they indicated a lack of vulnerability of the oscillator units to motion in general.

7. Recommendations for further study.

Since the initial warm-up and aging period of the oscillators is now over, and a backlog of behavior data has been accumulated, further investigation should produce more positive results. A repetition of the tests described in Section 3 would be in order, as would be further testing with the Sulzer D5 oscillators mounted in shock mounts.

Test periods should be at least 48 hours in length and, if time permits, each test should be preceded and followed by a similar amount of time with the oscillators in a normal position. Recording equipment utilizing 100-division paper should be used to record the phase comparator output so that with ten micro-seconds full-scale deflection, phase shift at 100 kilocycles may be read to one-tenth or one-twentieth of a micro-second.

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APPENDIX

A COMPUTER PROGRAM FOR FITTING A STRAIGHT LINE TO DATA POINTS AND COMPUTING THE STANDARD DEVIATION OF THE POINTS ABOUT THE FITTED LINE

[illegible]

[illegible]
[illegible]
[illegible]

```
      PROGRAM LINEFIT
C     THIS PROGRAM FINDS THE SLOPE AND Y-INTERCEPT OF THE BEST STRAIGHT
C     LINE (IN THE LEAST SQUARES SENSE) FITTED TO A SET OF DATA POINTS.
C     THE X DATA ARE ASSUMED TO BE WITHOUT ERROR. TRANSFORMATIONS TO
C     EITHER OR BOTH VARIABLES CAN BE MADE. THE PROGRAM WILL ALSO
C     COMPUTE THE STANDARD DEVIATION OF THE POINTS.
C         USAGE
C         1. CALLING SEQUENCE
C            MAIN PROGRAM. THE FOLLOWING DATA CARDS ARE READ.
C            A. FORMAT (3I4) - FIRST CARD
C               N, RIGHT-JUSTIFIED NUMBER OF DATA POINTS.
C               ICODEX, TRANSFORMATION CODES FOR X
C               ICODEY, TRANSFORMATION CODES FOR Y
C            B. FORMAT (12F6.0) - SUBSEQUENT CARDS.
C               X(1),Y(1),X(2),Y(2), ETC.
C            C. TRANSFORMATION CODES
C               =1  NONE
C               =2  VARIABLE REPLACED BY SQUARE ROOT OF VARIABLE
C               =3  VARIABLE REPLACED BY SQUARE OF VARIABLE
C               =4  VARIABLE REPLACED BY LOG TO BASE 10 OF VARIABLE
C               =5  VARIABLE REPLACED BY LOG TO BASE E OF VARIABLE
C     11111
C    TEST PERIOD FROM 1700 4 OCT TO 1300 7 OCT, S1, STATIC ONE, FINAL
      DIMENSION X(200),XSAVE(200),Y(200),YSAVE(200),YFIT(200),DIFFS(200
 104  READ 999, N, ICODEX, ICODEY
 999  FORMAT(3I4)
      PRINT 998,N,ICODEX,ICODEY
 998  FORMAT(4H1N =I4,3X8HICODEX =I2,3X8HICODEY =I2//)
      READ 100, (X(I),Y(I),I=1,N)
 100  FORMAT(12F6.0)
      DO 996 I=1,N
      XSAVE(I)=X(I)
 996  YSAVE(I)=Y(I)
      YSUM = 0.
      SUMX = 0.
      SUMY = 0.
      SUMXY = 0.
      SUMXX = 0.
      CALL TRANS(N,X,Y,ICODEX,ICODEY)
      XN = N
      DO 30 I = 1, N
      SUMX=SUMX+X(I)
      SUMY = SUMY+Y(I)
      SUMXX = SUMXX +      (X(I)*X(I))
  30  SUMXY=SUMXY+      (X(I)*Y(I))
      DENOM = XN*SUMXX-SUMX*SUMX
      ANUM = SUMY * SUMXX - SUMX * SUMXY
      A = ANUM / DENOM
      BNUM= XN*SUMXY-SUMX*SUMY
      B = BNUM / DENOM
      DO 40 J = 1,N
      YC = A + B * X(J)
      DIFF = Y(J) - YC
  40  YSUM = YSUM +      DIFF*DIFF
      S2 = YSUM / (XN - 1.)
      SIG=S2/DENOM
      SRA=SQRTF(SUMXX*SIG)
      SRB=SQRTF(XN*SIG)
      PRINT 997, A, B, SRA, SRB
 997  FORMAT(24H0  STRAIGHT LINE FITTING// 25H USING THE FORM Y=BX + A,
     1/ 4H A = E14.8/ 4H B = E14.8/ 26H STANDARD DEVIATION OF A = E14.8
```

```
     2/ 26H STANDARD DEVIATION OF B = E14.8)
      SUMFIT=.0
      SDIFFS=0.
      SDIFFSQ=0.
      DO 90 I=1,N
      YFIT(I)=B*X(I)+A
      DIFFS(I)=YFIT(I)-Y(I)
      SDIFFS=SDIFFS+DIFFS(I)
      SDIFFSQ=SDIFFSQ+DIFFS(I)**2
   90 SUMFIT=SUMFIT+ DIFFS(I)
  995 PRINT 99,SUMFIT,(X(I),YSAVE(I),Y(I),YFIT(I),DIFFS(I),I=1,N)
   99 FORMAT(9H0SUMFIT =E12.5///10X1HX14X1HY9X10HYTRANSPOSE8X4HYFIT11X5
     1DIFFS///(5E15.5))
      SIGMA=SQRTF((SDIFFSQ-SDIFFS**2/XN)/(XN -1.))
      PRINT 1000,SIGMA
 1000 FORMAT (1H0,7HSIGMA =E15.8)
      GO TO 104
 106  STOP
      END
      SUBROUTINE TRANS(N, X, Y, ICODEX, ICODEY)
      DIMENSION X(200), Y(200)
      GO TO ( 10, 20, 30, 40, 50), ICODEX
   20 DO 21 I = 1,N
   21 X(I)=SQRTF(ABSF(X(I)))
      GO TO 10
   30 DO 31 I = 1,N
   31 X(I) = X(I) * X(I)
      GO TO 10
   40 DO 41 I = 1,N
   41 X(I)=LOG10F(X(I))
      GO TO 10
   50 DO 51 I = 1,N
   51 X(I)=LOGF(X(I))
  10  GO TO (100, 200, 300, 400, 500), ICODEY
  200 DO 201 I = 1,N
  201 Y(I)=SQRTF(ABSF(Y(I)))
  100 RETURN
  300 DO 301 I = 1,N
  301 Y(I) = Y(I) * Y(I)
      RETURN
  400 DO 401 I = 1,N
  401 Y(I)=LOG10F(Y(I))
      RETURN
  500 DO 501 I = 1,N


  501 Y(I)=LOGF(Y(I))
      END
      END
```

N = 68 ICODEX = 1 ICODEY = 1

STRAIGHT LINE FITTING

USING THE FORM Y=BX + A,
A =-.90372827E+03
B =-.23075352E+01
STANDARD DEVIATION OF A = .13877674E+01
STANDARD DEVIATION OF B = .34962902E-01

SUMFIT = .10431E-06

X	Y	YTRANSPOSE	YFIT	DIFFS
.10000E+01	-.90400E+03	-.90400E+03	-.90604E+03	-.20358E+01
.20000E+01	-.91700E+03	-.91700E+03	-.90834E+03	.86567E+01
.30000E+01	-.91000E+03	-.91000E+03	-.91065E+03	-.65088E+00
.40000E+01	-.91000E+03	-.91000E+03	-.91296E+03	-.29584E+01
.50000E+01	-.92400E+03	-.92400E+03	-.91527E+03	.87341E+01
.60000E+01	-.91700E+03	-.91700E+03	-.91757E+03	-.57348E+00
.70000E+01	-.91000E+03	-.91000E+03	-.91988E+03	-.98810E+01
.80000E+01	-.93100E+03	-.93100E+03	-.92219E+03	.88114E+01
.90000E+01	-.93100E+03	-.93100E+03	-.92450E+03	.65039E+01
.10000E+02	-.93100E+03	-.93100E+03	-.92680E+03	.41964E+01
.11000E+02	-.93100E+03	-.93100E+03	-.92911E+03	.18888E+01
.12000E+02	-.93100E+03	-.93100E+03	-.93142E+03	-.41869E+00
.13000E+02	-.93100E+03	-.93100E+03	-.93373E+03	-.27262E+01
.14000E+02	-.93100E+03	-.93100E+03	-.93603E+03	-.50338E+01
.15000E+02	-.93800E+03	-.93800E+03	-.93834E+03	-.34130E+00
.16000E+02	-.94400E+03	-.94400E+03	-.94065E+03	.33512E+01
.17000E+02	-.94400E+03	-.94400E+03	-.94296E+03	.10436E+01
.18000E+02	-.94400E+03	-.94400E+03	-.94526E+03	-.12639E+01
.19000E+02	-.94400E+03	-.94400E+03	-.94757E+03	-.35714E+01
.20000E+02	-.94400E+03	-.94400E+03	-.94988E+03	-.58790E+01
.21000E+02	-.95800E+03	-.95800E+03	-.95219E+03	.58135E+01
.22000E+02	-.96500E+03	-.96500E+03	-.95449E+03	.10506E+02
.23000E+02	-.96500E+03	-.96500E+03	-.95680E+03	.81984E+01
.24000E+02	-.95800E+03	-.95800E+03	-.95911E+03	-.11091E+01
.25000E+02	-.96500E+03	-.96500E+03	-.96142E+03	.35833E+01
.26000E+02	-.95800E+03	-.95800E+03	-.96372E+03	-.57242E+01
.27000E+02	-.96500E+03	-.96500E+03	-.96603E+03	-.10317E+01
.28000E+02	-.96500E+03	-.96500E+03	-.96834E+03	-.33393E+01
.29000E+02	-.97200E+03	-.97200E+03	-.97065E+03	.13532E+01
.30000E+02	-.96500E+03	-.96500E+03	-.97295E+03	-.79543E+01
.31000E+02	-.97900E+03	-.97900E+03	-.97526E+03	.37381E+01
.32000E+02	-.97200E+03	-.97200E+03	-.97757E+03	-.55694E+01
.33000E+02	-.97900E+03	-.97900E+03	-.97988E+03	-.87693E+00
.34000E+02	-.96500E+03	-.96500E+03	-.98218E+03	-.17184E+02
.35000E+02	-.97900E+03	-.97900E+03	-.98449E+03	-.54920E+01
.36000E+02	-.99300E+03	-.99300E+03	-.98680E+03	.62005E+01
.37000E+02	-.98600E+03	-.98600E+03	-.98911E+03	-.31071E+01
.38000E+02	-.99300E+03	-.99300E+03	-.99141E+03	.15854E+01
.39000E+02	-.98600E+03	-.98600E+03	-.99372E+03	-.77221E+01
.40000E+02	-.99300E+03	-.99300E+03	-.99603E+03	-.30297E+01
.41000E+02	-.99300E+03	-.99300E+03	-.99834E+03	-.53372E+01
.42000E+02	-.99300E+03	-.99300E+03	-.10006E+04	-.76447E+01

.43000E+02	-.10000E+04	-.10000E+04	-.10030E+04	-.29523E+01
.44000E+02	-.10000E+04	-.10000E+04	-.10053E+04	-.52598E+01
.45000E+02	-.10070E+04	-.10070E+04	-.10076E+04	-.56736E+00
.46000E+02	-.10140E+04	-.10140E+04	-.10099E+04	.41251E+01
.47000E+02	-.10070E+04	-.10070E+04	-.10122E+04	-.51824E+01
.48000E+02	-.10140E+04	-.10140E+04	-.10145E+04	-.48996E+00
.49000E+02	-.10280E+04	-.10280E+04	-.10168E+04	.11203E+02
.50000E+02	-.10280E+04	-.10280E+04	-.10191E+04	.88950E+01
.51000E+02	-.10210E+04	-.10210E+04	-.10214E+04	-.41257E+00
.52000E+02	-.10280E+04	-.10280E+04	-.10237E+04	.42799E+01
.53000E+02	-.10210E+04	-.10210E+04	-.10260E+04	-.50276E+01
.54000E+02	-.10210E+04	-.10210E+04	-.10283E+04	-.73352E+01
.55000E+02	-.10350E+04	-.10350E+04	-.10306E+04	.43573E+01
.56000E+02	-.10350E+04	-.10350E+04	-.10330E+04	.20498E+01
.57000E+02	-.10420E+04	-.10420E+04	-.10353E+04	.67422E+01
.58000E+02	-.10420E+04	-.10420E+04	-.10376E+04	.44347E+01
.59000E+02	-.10420E+04	-.10420E+04	-.10399E+04	.21272E+01
.60000E+02	-.10420E+04	-.10420E+04	-.10422E+04	-.18038E+00
.61000E+02	-.10420E+04	-.10420E+04	-.10445E+04	-.24879E+01
.62000E+02	-.10420E+04	-.10420E+04	-.10468E+04	-.47955E+01
.63000E+02	-.10420E+04	-.10420E+04	-.10491E+04	-.71030E+01
.64000E+02	-.10490E+04	-.10490E+04	-.10514E+04	-.24105E+01
.65000E+02	-.10560E+04	-.10560E+04	-.10537E+04	.22819E+01
.66000E+02	-.10630E+04	-.10630E+04	-.10560E+04	.69744E+01
.67000E+02	-.10690E+04	-.10690E+04	-.10583E+04	.10667E+02
.68000E+02	-.10630E+04	-.10630E+04	-.10606E+04	.23593E+01

SIGMA = .56589160E+01